Department of Mechanical Engineering

Community-scale

Integrated Solid Waste Management System

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Abstract

Landfilling of non-separated municipal solid waste (MSW) is the widely used waste management method due to its simple processes and low cost. However, landfilling is regarded as unsustainable because of its significantly harmful impacts on the environment. Consequently, the integrated solid waste management (ISWM) system with Waste-to-Energy (WtE) technology is considered to be the most suitable waste management option.

The purpose of this research is to focus on the analysis of a community-scale ISWM system, which has more advantages than larger scale systems in term of the environmental footprint. It also encourages the management by local authorities. The research objectives are to demonstrate that this community-scale ISWM is viable, although the smaller scale is limited by higher cost per ton of waste than the larger scale. This research also investigates the most suitable waste management option by modelling the different scenarios of ISWM system of the general small-community case study. The modelling is focussed on the case study that can reflect the situation of a community with a high economic rating.

The results of this research demonstrate that the designed ISWM system, with the intensified extent of treatment facilities, has the most environmental benefits with acceptable cost. The mentioned designed waste management scenario is modelled using an anaerobic digestion (AD) facility for treating biowaste, mixed dry recyclables (MDR) sorting for recyclable waste and aerobic mechanical-biological pre treatment (MBP) facility for treating residual waste.

The assessment also shows that the MDR sorting facility is the most significant treatment option that influences the environmental benefits of the ISWM system. In addition, relative low capital and annual cost per tons of waste of the MDR sorting facility compared to the AD and aerobic MBP facility also make this treatment option the most important in the ISWM system.

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CHAPTER 1: INTRODUCTION

Municipal solid waste management is considered as a critical problem in the UK. Landfilling is still the predominant management option because of less initial capital and operating cost than the other options. However, landfilling is regarded as unsustainable due to its harmful impacts on the environment. In the past, waste generation rates were far less than at present and the distance to disposal sites were within reasonable distances. However, according to the large amount of waste generated per year in each community, the rapidly high increasing land use for landfilling and the higher concerns in health and environmental impacts, landfilling is the waste management option that should be eliminated.

If landfilling is no longer suitable in the current situation, so the other management options must be considered. Reuse or recycling is one of the best options for reducing the amount of waste. But in the capitalised and globalized world in which development is cannot even pause for only a second, waste generation rate seems to be higher and higher, which cannot be deal with only the reuse and recycle strategies. In this case, energy recovery from waste seems to be the most suitable and recommended option (Department for Environment Food and Rural Affairs - DEFRA, 2007a).

Waste-to-Energy (WtE) technology can be installed for large scale or smaller scale within communities. Although small-scale WtE Technology is limited by higher cost per ton of waste than the bigger scale, the benefits of using this small scale facility within communities make them a viable option. Small-scale facilities have a more advantage in environmental footprint compared with large-scale deployments and also encourage the management by local authorities. Community level power generation may avoid grid connection and planning obstacles that pose barriers to larger facilities. The efficiencies of community WtE systems are increased by the availability of a consumer base for heat utilisation (Adu-Gyamfi et al., 2010).

The purpose of this project is to focus on the study of small scale municipal solid waste management using the concept of Waste-to-Energy. This includes the investigation of the most suitable integrated option of small scale WtE technology for local communities, the estimation of municipal solid waste (MSW) for general small community model, finding the most suitable separation method for this MSW and the design of the most suitable integrated WtE system for managing this MSW.

CHAPTER 2: LITERATURE REVIEW

As mentioned in the introduction, this study focuses on an analysis of the community-scale Integrated Solid Waste Management (ISWM) system including with provides some impact assessment on the example model. Therefore this chapter provides information related to the modelling of ISWM System for community level which started with the estimation of waste generation for the community level, by using a previous study of waste generation model. The whole process of ISWM is also defined using Life Cycle Analysis (LCA) method. The state of the art of the Waste-to Energy (WtE) technology for solid waste treatment is either mentioned in this section. This chapter also provides the details of the tool – LCA-IWM assessment tool – that is used for making an analysis of our model case study.

2.1 Waste-to-Energy Policy – UK

According to DEFRA (2007b), the UK Government wants to expand the recovery of energy from residual waste that unavoidably will be disposed to landfill in order to provide the greater contribution to energy policy. Greater recovered energy from food waste by using anaerobic digestion is also needed to promote by the government in order to obtain the benefits from energy aspect and carbon saving.

The UK government has no specific target of waste that is expected to go for energy recovery. However, municipal solid waste (MSW) is set a target as to be recovered by recycling, composting and energy recovery process. Recycling and composting of household waste are also set as targets by the UK government, while the government would like to exceed both of these targets if possible, meeting them precisely would mean an increase in energy recovery to about 25% of municipal waste in 2020 compared to around 10% today (www.parliament.uk, 2007).

Waste-to-Energy (WtE) technologies include biological process (Anaerobic Digestion, AD), direct combustion (incineration), use of secondary recovered fuel (Refuses Derived Fuel, RDF - an output from mechanical and biological treatment processes), pyrolysis, gasification and plasma arc heating. Each of these mentioned WtE technologies is not regarded by the UK government as the more preference over the others, with the exception of treating food waste by using AD. Selection of a suitable technology may vary reflecting the needs of the local situation. However, greenhouse gas emission is a major consideration regarded by the UK government in case of developing WtE plants.

WtE technologies have many concerns by the publics over environmental and health threads. These issues are most frequently mentioned regarded to incinerators. Nevertheless, many researches which have done up to date show no credible evidence of adverse health outcomes for those living near incinerators (DEFRA, 2007b). In addition, the emissions from MSW incineration have fallen in recent years according to the strict emission standards which currently applied through the Waste Incineration Directive. For example, according to the Health Protection Agency, the incineration of municipal solid waste accounts for less than 1% of UK emissions of dioxins. The UK experience of significant falls in pollutants has also been seen in other European countries such as Germany, which apply the same standards (DEFRA, 2007b).

However, according to the Waste Strategy for England published in May 2007, it is found that incineration is not mentioned or recommended in this strategy for treating waste stream. It strongly supports using AD to treat food waste and sets targets to increase recycling for recyclable waste. It showed that, according to the recent research, AD has significant carbon and energy benefits over other options for managing food waste - and may be particularly cost effective for food waste if separately collected (Guildford Anti Incinerator Network - GAIN, 2009). It also stated in the strategy that the government wishes to encourage more consideration of the use of AD, both by local authorities and businesses (Friends of the Earth, 2007 and DEFRA 2007a). Therefore, in this paper, it wishes to encourage more consideration of anaerobic digestion for use as the WtE technology in the Integrated Solid Waste Management (ISWM) system.

2.2 Waste Generation Model for Community Level

Waste management models which have been developed over the last decades have paid an intention on increasing of the integration modules of related processes with consideration given to environmental, economic and social aspects. The recent waste management models are able to evaluate the entire waste management systems using quantitative and qualitative criteria consideration. The impacts of demographic, social and economic dynamics, as well as other factors are also taken into account (Beigl et al., 2004).

2.2.1 Classification of Waste Generation Model

Because of the diversity of MSW generation ways and the various waste streams of MSW, the characterisation of related parameters is very complicated. The study by Beigl et al. (2004) describes previous approaches of waste generation model which can be classified by the model type:

- **Input-output models**

The input of the waste generator is assessed by using production, trade and consumption data about products related to the specific waste streams.

- **Factor models**

These models focus on an analysis of the factors, which describe the processes of waste generation. Examples of proved parameters are e.g. the income of households, dwelling types or the type of heating

According to these types of model study, only a few methodological procedures came into consideration for application within the aimed forecasting model for cities or communities. This was due to the following reasons (Beigl et al., 2004):

- **Level of aggregation**

The identification of parameters has to be based on a database, which describes regional peculiarities. The exclusive use of national aggregates in input output model is not appropriate for explaining regional dynamics. Therefore, preference was given to factor models that focus on socio-economic and demographic indicators.

- **Predictability of parameters**

The selection of model parameters has to prioritise parameters at the city level, which can be forecasted with a relatively high accuracy and a long forecasting horizon. Examples of such parameters with high inertia are the population age structure, household size or infant mortality rate (Beigl et al., 2004 and Lindh, 2003).

- **Applicability**

Applicability refers to the user-friendliness of the aimed forecasting tool. Therefore methods that provide easily available, standardised secondary data have to be favoured over elaborate and time-consuming qualitative approaches such as the Delphi method (Beigl et al., 2004 and Karavezyris, 2001).

Based on these considerations, the amount and composition of municipal solid waste were hypothesised which were dependent upon easily available socio-economic and demographic parameters.

2.2.2 Municipal Solid Waste Generation Model in European Cities

In this paper, the municipal solid waste generation model in the European region, developed by Beigl et al. (2004), will be adopted to use in making further analysis.

The development of the mentioned model was designed for the assessment of the future municipal waste streams of major European cities. The selection of the applied approach was based on recent forecasting methodology developed by Armstrong (2001). The different methodological approaches were selected for assessing two modules, consisted of the MSW generation rate and the MSW composition, which can be used for estimating the total amount of MSW and the mass percentage of main waste streams generated in the future assessment year.

Figure 1 shows the compositions of the overall mentioned model. This model uses the different function for the calculation for the different prosperity level of the defined cities. The defined cities will be characterised into one of the prosperity level by using the related socio-economic and development indicators, i.e. Gross Domestic Product (GDP) and infant mortality rate.

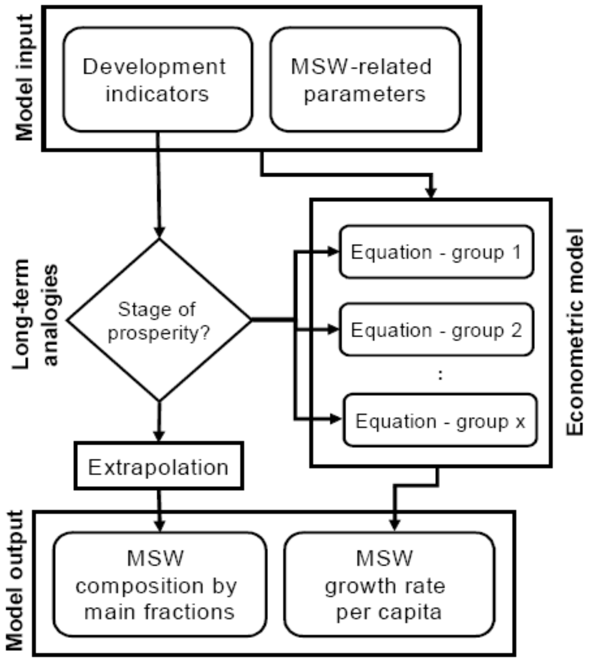

Figure 1: Waste Generation Model

Source: Beigl et al., 2004

The MSW generation module is an econometric model. The function for calculation consists of four different multiple linear equations for each four prosperity groups of cities. The classical econometric process was used instead of the vector autoregression (VAR) process because of the limited time series available. (Beigl et al. 2004)

Due to the remarkable differences between MSW generation rates and growth rates in European cities, the several approaches were implemented to identify significant indicators that impact on the generation and composition of MSW. As an example (Beigl et al., 2004), a comparison of economic areas in the year 2000 shows that major European Union-15 (EU-15) cities were characterised by far higher MSW generation rates (510 kg/cap/yr) than the Central and East European (CEE) cities (354 kg/cap/yr), while from 1995 to 2001 annual growth in CEE cities is more than twice as high (4.3%) as in cities of EU-15 countries (1.8%). Therefore several bivariate and multivariate statistical analyses were carried out to identify indicators with a significant impact on MSW generation and composition.

Table 1 show the considered development and socio-economic indicators in the study of Beigl et al. (2004), which were available for both community and national level.

Table 1: Available Development and Socio-economic Indicators.

Available indicators at city and national level	
• Population	• Population density
• Population age structure (0 to 14 years / 15 to 59 years / 60 and more years)	• Sectoral employment (Agriculture / Industry / Services)
• Gross domestic product	• Infant mortality rate
• Overnight stays	• Life expectancy at birth
• Average household size	• Unemployment rate

Source: Beigl et al., 2004

The study by Beigl et al. (2004) has conducted the analysis of the waste generation model dependent on the above socio-economic indicator by using the hypothesis analysis. The result shows that four national development indicators, as be seen in Table 2, were selected as cluster criteria in order to explain this prosperity level variable.

Table 2: Municipal solid waste generated and development indicators

National development indicators and MSW generation	**Prosperity level**			
	Low	**Medium**	**High**	**Very high**
Gross domestic product per capita[1]	5841	11400	19418	21317
Infant mortality rate[2]	15.0	8.7	7.6	5.5
Labour force in agriculture (%)	24.0	18.7	4.8	3.2
Labour force in services (%)	44.4	52.2	59.4	66.2
Municipal solid waste (kg/cap/yr)	287	367	415	495

1 USD Purchasing power parities at 1995 prices
2 Per 1,000 births

Source: Beigl et al., 2004

Table 2 shows the socio-economic indicators of each prosperity level and the assumed MSW generation rate that can prove the relationship from the hypothesis analysis. Municipal waste is generated with low rates along with low gross domestic products, high infant mortality rates.

The estimated equations of the final MSW generation model for communities are represented as following (Beigl et al., 2004). The initial consideration included the indicators listed in Table 1. The final model was selected by backward regression using the ordinary least squares method.

For cities with very high prosperity;

$$MSW^t = 359.5 + 0.014 \times GDP^t - 197.1 \times \log\,(INF_{urb}^t) \qquad (1)$$

For cities with high prosperity;

$$MSW^t = 276.5 + 0.016 \times GDP^t - 126.5 \times \log\,(INF_{urb}^t) \qquad (2)$$

For cities with medium or low prosperity;

$$MSW^t = -360.7 - 375.6 \times \log(INF_{nat}^t) + 8.93 \times POP_{15-59}^t - 123.9 \times HHSIZE^t + 11.7 \times LIFEEXP^t \qquad (3)$$

Where,

- MSW^t is the municipal solid waste generated per capita and year,
- GDP^t is the national gross domestic product per capita at 1995 purchasing power parities,
- INF is the infant mortality rate per 1,000 births in the city (INF_{urb}) or in the country (INF_{nat}),
- POP_{15-59}^t is the percentage of the population aged 15 to 59 years,
- $HHSIZE^t$ is the average household size and
- $LIFEEXP^t$ is the life expectancy at birth and t is the year.

As mentioned that the calculated functions in the model are based on the different four prosperities. Concerning the definition of these prosperity levels, Table 3 shows the approximate threshold values for three national indicators among the different prosperities of the city groups.

Table 3: Approximate Threshold Values between City Groups (National Indicators)

Prosperity Level	Gross domestic product[1]	Infant mortality rate[2]	Labour force in agriculture (%)
Low			
	7,100	12.0	21.4
Medium			
	13,800	8.1	10.5
High			
	20,200	6.3	4.0
Very high			

1 USD Purchasing power parities at 1995 prices
2 Per 1,000 births

Source: Beigl et al., 2004

The indicators mentioned in the above Table 3 which are regarded as the significant factors to the impact on MSW generation are described below.

- **Gross domestic product**

This regularly used indicator is the significant factor in cities with a high prosperity rather for cities with a lower economic growth. This is due to the inequality of high regional income in the CEE countries (Beigl et al., 2004 and Förster et al., 2002). This reason result in a huge different between the mean values compared with the lower median values which provide the significant effect.

- **Social indicators**

Infant mortality rate and life expectancy are never used in the previous study as the parameters that effect to the model. However, these social indicators provide a significant impact to the GDP. They can be used for providing the regional welfare and also have the good availability and high quality of data including with the good predictability.

- **Age structure**

The relationship between the MSW generation rate and the group of the percentage of the medium age are confirmed by the previous studies by Sircar et al. (2003) and Lindh (2003) (Beigl et al., 2004).

- **Household size**

This parameter can provide the negative impacts to the MSW generation rate on a regional scale which can be confirmed in the study by Dennison et al. (1996).

2.3 Integrated Solid Waste Management System - ISWM

Sustainable management of MSW demands an integrated approach based on the waste management strategy shown in figure 2. It is unlikely that the only single option of waste management is sufficient to deal with the current problem of MSW. Therefore, the integrated solid waste management (ISWM) system is must be considered. The example of ISWM is shown in figure 3. It is obviously that the first and the most preferable option is prevention and reduced generation of MSW. Waste prevention is closely linked with influencing consumers to demand greener products and less packaging (Azapagic et al., 2005).

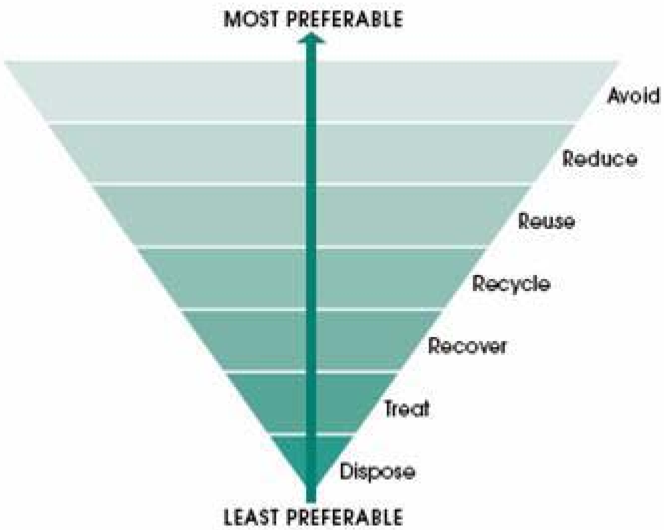

Figure 2: Integrated Solid Waste Management Strategy

Source: Campbell Town City Council, 2010

Instead of prevention and reduced generation of MSW, materials recovery is also the significant option of the ISWM. Many countries have introduced recycling targets for material recovery. For example, according to Azapagic et al. (2005), the European Commission has defined recovery and recycling targets for packaging waste (European Commission, 1994), end-of-life vehicles (European Commission, 2000) and electrical and electronic waste (European Commission, 2003). The further option for material recovery is aerobic composting of organic waste, which includes food and garden waste. The material recovered from this process is soil conditioners and fertiliser (with added processes).

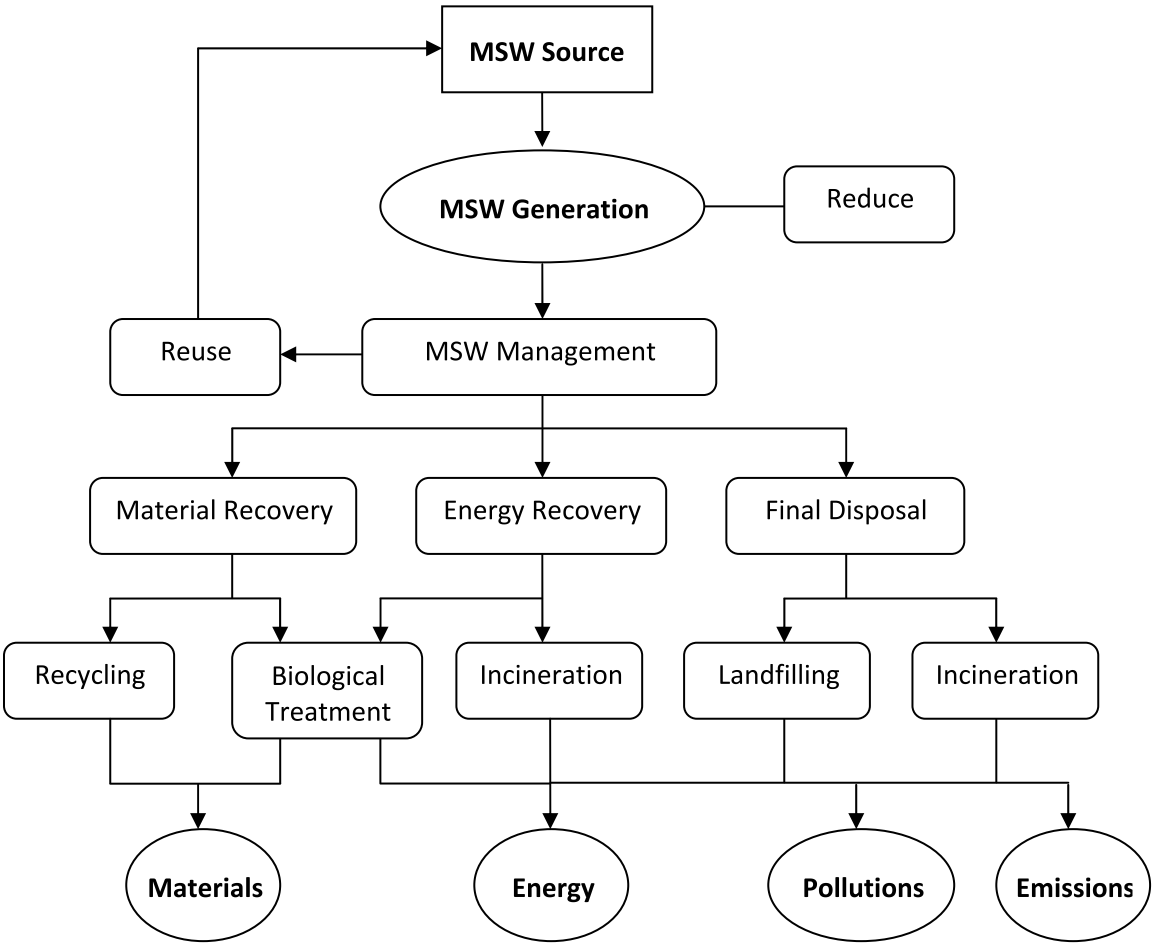

Figure 3: Integrated Solid Waste Management Options

Source: Azapagic et al., 2005 and Romero-Hernandez et al., 2003

The next step in the ISWM strategy is energy recovery which contains anaerobic digestion of organic waste, which generates biogas that can be used to generate either heat or electricity, and incineration which can generate heat or electricity or both.

The final step is disposal of waste. Both options which are landfill and incineration without energy recovery should be used in a limited and highly concerned because of their potential to cause environmental damage.

It is also important to bear in mind that, instead of the disposal of waste, the other steps of ISWM can also generate some environmental impact, due to related activities such as collection, transportation and recycling processes. Therefore, life cycle analysis (LCA) theory is very significant for making an assessment of the impacts of ISWM to each individual aspect such as environmental or economic.

2.3.1 Life Cycle Analysis (LCA) of ISWM

Life cycle analysis of the ISWM system is used as the tool to identify the impacts associated with each of waste management alternatives from ‘cradle to grave’ in order to help to make an assessment (Azapagic et al., 2005). The LCA of ISWM is outlined in Figure 4.

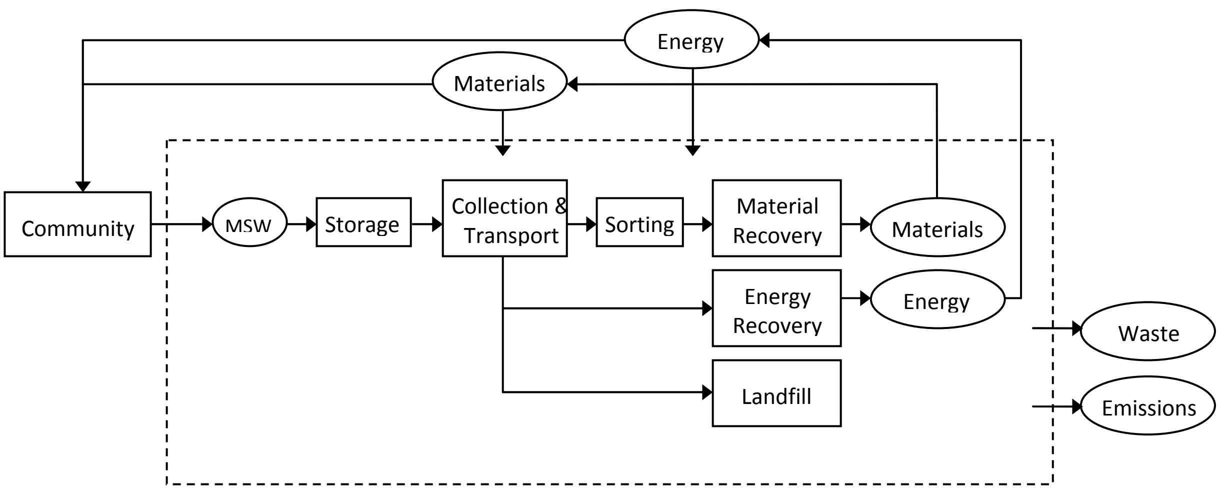

Figure 4: Life Cycle of ISWM

Source: Azapagic et al., 2005

The assessment begins since waste is put across the boundary via a storage scheme (bags, bins and containers). Then MSW is collected and delivered to the treatment facility – which includes sorting, material and energy recovery – and disposal site. The flows of other products recovered from waste treatment, i.e. material recovered, energy produced and compost derived from organic waste are considered in the assessment as well. The generation of these products is regarded as benefits.

The impact assessment can be divided into such as environmental, social and economic aspects. The assessment of environmental impact is linked with the pollutant emissions and the consumption of resources within the system. The impacts arising at the construction phase are excluded from assessment. For the economic assessment, the cost of the system is concerned which includes investment in waste containers, collection and transport vehicles and treatment plants.

2.3.2 MSW Management in Europe

The EU countries generate in total around 250×10^6 t of MSW each year (Azapagic et al., 2005). The design of a waste management system in the EU is based on the waste management strategy described in section 2.3. Table 4 shows the amount and composition of waste in different EU countries. However, there is some variation in waste management priorities within the EU countries. For example, the northern European countries give the recovery of materials a higher priority than energy recovery, while the other country such as France considers them as equal. The percentage of MSW management variation among some countries in EU is shown in Figure 5.

Table 4: MSW generation and composition by weight in Europe in 1999 or latest available year (European Commission, 2003)

	Amount 1,000 t	**Paper**	**Textiles**	**Plastics**	**Glass**	**Metals**	**Food and Garden Waste**	**Other**
Belgium	5,462	17	4	6	3	4	20	46
Greece	3,900	18	4	10	3	3	51	11
Spain	24,470	21	5	11	7	4	44	8
France	37,800	25	3	11	13	4	29	15
Ireland	1,933	33	2	10	6	3	24	22
Netherlands	9,359	28	2	5	6	3	39	17
Austria	5,270	24	3	15	9	7	29	13
Finland	2,510	33	2	3	2	5	33	22
Norway	2,650	36	4	9	3	4	30	14
Bulgaria	3,197	11	4	7	6	4	41	27
Cyprus	369	29	7	12	1	2	42	7
Czech Republic	3,365	8	2	4	4	2	18	62
Hungary	4,376	20	5	15	4	3	31	22
Latvia	292	14	3	7	8	4	48	16
Lithuania	1,236	1	1	0	2	19	40	37
Romania	5,699	18	6	10	6	5	53	2
Slovak Republic	1,700	13	3	9	6	8	26	35
Slovenia	1,024	15		10	5	7	32	31

Source: Azapagic et al., 2005 based on European Commission, 2003

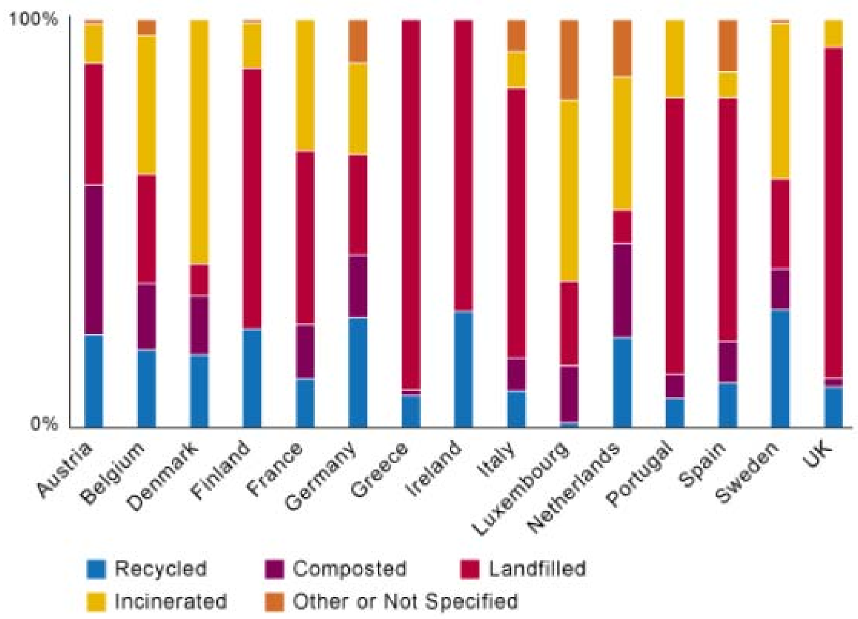

Figure 5: MSW management in the EU

Source: Azapagic et al., 2005 based on European Commission, 2003

As seen in Figure 5, UK waste management has the main MSW treatment process based on landfilling which is much higher than other countries in EU such as Denmark, Netherlands, Sweden and Switzerland. This also demonstrates the lack of energy recovery from waste in the waste management strategy in the UK.

According to the study by Azapagic et al. (2005), the waste management is legislated extensively at the EU level and legislation is based on the following main principles, known as five PS (European Commission, 2003),

1. Prevention principle: waste prevention and minimisation should be given the highest priority.
2. Proximity principle: Waste should be disposed of as close as possible to where it is produced.
3. Producer responsibility principle: waste producers should bear full cradle to grave responsibility for any damage caused by the waste that they produce.
4. Polluter pays principle: Polluters and waste producer, rather than society in general, should bear the full cost of the safe management and disposal of waste.

5. Precautionary principle: waste management strategies should not pose risk (if there is even small chance of a major problem, then that option should be avoided).

Some examples of the EC legislation in the area of waste management include the directives on environmental impact assessment, incineration, landfilling, packaging waste, electronic and electrical waste equipment and end-of-life vehicles.

The EU waste directives and waste laws of many EU member countries are linked to the planning processes. Therefore, most of waste management programmes need permission from the authority which vary between each countries in EU. For example, most decisions are made by the local authorities for the region where the planning application has been made, while in France this process is usually centralised.

2.4 MSW Management System - WtE Technology

This section in the literature review provides the definition of WtE system and widely used technology. Thereafter, the specific information focus on the interested WtE technology which will be used for making an analysis in the case study model in this paper will be mentioned in the research model description section.

Waste-to-energy (WtE) refers to any waste treatment that creates energy in the form of electricity or heat. The other fuel products such as hydrogen or ethanol can be the output from more advanced WtE processes. WtE technology can reduce problems and costs of disposal to landfill and provide the benefits on environmental and renewable energy aspects. Modern WtE technologies can be broadly classified as thermal, biochemical or chemical processes. The information on each technology in this paper provided below is based on the research of Wagner (2007).

2.4.1 Thermal processing

Combustible waste such as organic, papers and cardboards can be the input waste streams for the thermal processing which can produce heat or various liquid or gaseous fuels. The options of this process can be broadly classified into four main technologies.

- **Combustion or direct incineration**

Waste management system by using incineration in the past does not have the modern gas emission treatment and the recovery process of energy or materials which provides the environmental impacts by the toxic emission and the zero energy recovery from the wasted resource. This reason results in the suspension by the OECD countries. There are various emerging technologies that are able to produce energy from waste with high standard of gas emission treatment. These technologies are considered to generate renewable energy and are widely perceived to be more publicly acceptable than recent incineration.

- **Gasification**

Gasification process is the restricted air supply incineration. The air-deficient environment in this gasification process results in the conversion of biomass and plastic into a synthesis gas. The synthesis gas has approximately 10-15% heating value of natural gas which can be used directly or converted to synthetic gasoline and methanol. The combination of gasification and the production of electricity process is economically and environmentally approved by the recent studies. However, the suitable input waste stream is clean biomass such as wood waste.

- **Pyrolysis**

This process is the chemical decomposition of organic materials in the free-oxygen environment. Combined pyrolysis-combustion and combined pyrolysis- gasification have been developed in the pilot scale, however, there is currently no implementation in the real situation. Although this technology is being developed, the experiment by using plastics and mixed MSW as an input waste streams has considerably high energy efficiency.

- **Plasma arc waste disposal**

This process is partially the same as the gasification process with using an electrical arc to break the materials in the waste stream. The electricity with high voltage and ampere is passed into two electrodes to create the electrical arc in order to generate high temperature and high electrical energy. Inert gas is passed through the arc into a sealed containment, containing input waste stream, which has the temperature equal to approximately 4000°C. At this temperature, most types of waste are broken into basic elemental components in a gaseous form, and complex molecules are atomized.

2.4.2 Bio-chemical processing

Bio-chemical process of WtE system is a method that organic waste is broken down and converted into the useful products. The process occurs by the action of bacteria either in the environment with oxygen or without oxygen.

- **Anaerobic digestion**

Anaerobic digestion (AD) occurs in the free-oxygen situation which produces methane, carbon dioxide and hydrogen sulphide and water, while aerobic digestion produces carbon dioxide and water. Anaerobic digestion (AD) in the MSW treatment system is preferred for organic waste because this kind of waste is easily degradable. Anaerobic digestion is a reliable technology for the treatment of food waste, garden waste and agricultural waste. Biogas produced by AD can be used in order to produce both electricity and heat, and digestate which can be used to produce fertilizer or soil-conditioner (Verma, 2002). However, anaerobic digestion technology, the same as many technologies, has not only advantages but it has many disadvantages part as well. There may be some risks to human health with the pathogen which occur during the fermentation process, but it can be avoided with appropriate sanitary plant design. In addition, the financial aspect of anaerobic digestion technology includes construction cost and operation cost. Construction cost is high but the source of income which comes from the sale of electricity and fertilizer can make this technology more acceptable.

- **Refuse derived fuel**

Composite materials of MSW vary according to different location. General MSW has low heat value, high ash and moisture content which provide the problems for using this non-separated MSW as a fuel. Therefore, developing of the technologies that produce refuse derived fuel (RDF) from the high calorific content of MSW can provide some benefits over this problem.

Non-combustible and low calorific content of MSW need to be sorted before RDF processing. Processing of RDF consists of the procedures that compact waste at high temperatures and very pressures. RDF is usually for making as pellet or briquette which can be used in boilers or in fluidised bed incinerations. It is important to note that using processed waste (where recyclable and non combustible components have been removed), for power generation will dramatically increase the efficiency of the waste to energy process, but at an increased cost due to the increased handling of the product.

- **Fermentation**

This process uses the fermentation by bacteria to convert carbohydrates in the organic materials into ethanol. This process is suitable for treating organic waste. The input materials for this fermentation technology which is widely used are agriculture waste such as molasses. However, the recent developments try to focus on organic material in MSW such as food waste and sewage.

2.4.3 Chemical treatments

- **Esterification**

Esterification can generate useable fuels in the form of biodiesel by using waste oil as an input material. This chemical process cannot be used for treating solid material. The methods of biodiesel generation from waste oil can be broadly classified into three main parts (Drewette et al., 2007).

- Base catalysed transesterification of the oil;
- Direct acid catalysed transesterification of the oil, and;
- Conversion of the oil to its fatty acids and then to biodiesel.

The catalysed transesterification method is widely used because it is the most economically viable process which needs only low temperatures and pressures in the process and can contribute up to 98% conversion yield. By-product, which is the glycerol, from the process can be sold or purified as the materials input for pharmaceutical and cosmetic industries. Biodiesel is regarded as the alternative renewable fuel that has less toxic and more degradable than conventional fossil fuel which can be used as the fraction for blending with the petroleum diesel for fuelling.

2.5 LCA-IWM Assessment Tools

The LCA-IWM Assessment Tool is a decision support tool for planning of municipal solid waste (MSW) management developed in the project 'The use of life cycle assessment tools for the development of integrated waste management strategies for cities and regions with rapid growing economies' which is supported by the European Commission under the Fifth Framework Program of energy, environmental and sustainable development (EESD) (Darmstadt University of Technology, 2005).

Modelling of different scenario of MSW management at the municipality level is available in this LCA-IWM assessment tool. There are several modules in this tool which represent individual processes of MSW management, i.e. temporary storage, collection, transportation and waste treatment. Environmental, economic and social assessments are available in the assessment module of this LCA-IWM tool which uses sustainability criteria and quantitative indicators to calculate the output results. These input indicators for calculation are the inventory data such as emissions for the environmental assessment and costs for the economic assessment which are derived from each waste management modules available in the tool.

2.5.1 Background modules

Figure 6 depicts a general overview of the background modules existing in the LCA-IWM Assessment tool. It includes all processes related to the Integrated Solid Waste Management (ISWM) system which started since the generation until the disposal of waste stream. The background modules consist of Temporary Storage, Collection, Transportation, Treatment and Disposal. These stages in the background modules represent the paths which the user of this tool can select for each scenario. The assessment module in this tool is identified based on the data input in the background modules.

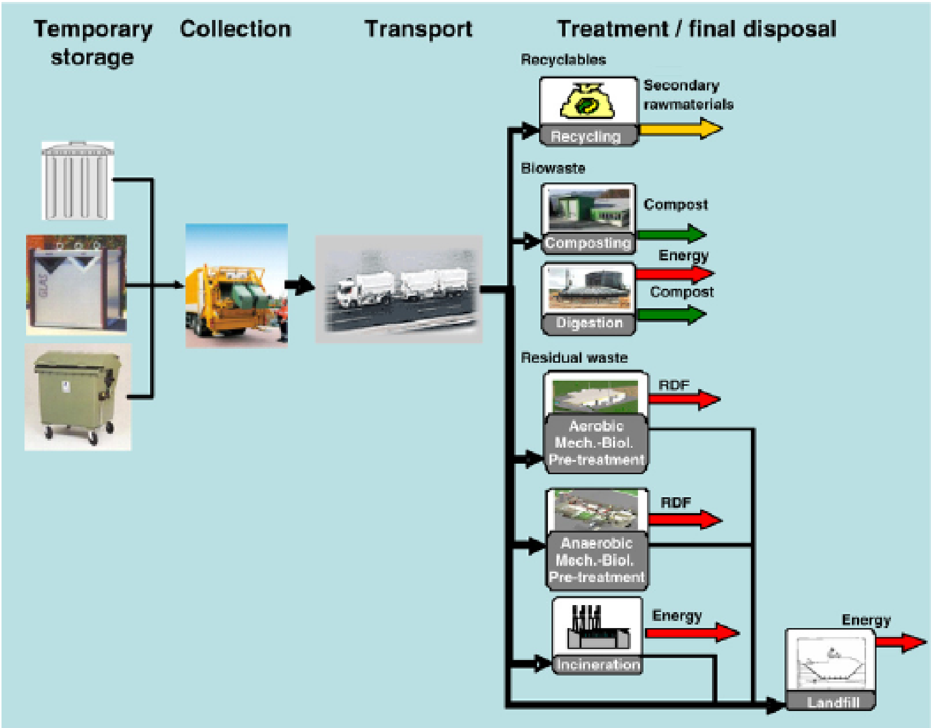

Figure 6: An Integrated Waste Management System in the LCA-IWM Assessment Tool

Source: den Boer et al., 2007

More information about the background modules in this LCA-IWM assessment tool which consist of the assumption, defined methodology and calculation methods of each stage in the background modules are provided in the Appendix I.

2.5.2 Assessment Modules

The goal of the assessment modules in the LCA-IWM tool is to provide the result that can enable the making of sustainable decisions in waste management planning. Therefore, all economic, social and environmental aspects are included in this assessment. The result from the assessment modules are displayed separately into environmental, economic and social impacts. The borders of the assessment modules include all of the impacts that occur at all stages of background modules.

2.5.2.1 Environmental Assessment

The objectives of the environmental assessment in the LCA-IWM tool are to achieve the environmental sustainability. Environmental sustainability in solid waste management can be summarized into conservation of resources and pollution prevention. Thus, in this tool, environmental assessment will be specified through defining criteria and quantitative indicators to measure environmental sustainability of alternative ISWM scenarios (den Boer et al., 2005).

- **Selection of environmental criteria**

The selection of criteria for the environmental assessment in the LCA-IWM assessment tool was based on the life cycle impact assessment (LCIA) method, and the targets of the European waste policy. The impact categories which are selected to be used in the assessment based on LCIA method are shortly introduced below. More detail description of these criteria including with the calculation method can be found in Appendix II.

  - **Abiotic Depletion**

    Abiotic resources are regarded non-living natural resources such as crude oil, ore and others. Abiotic depletion means the depletion of abiotic resources which depends on the quantity of resources which is ultimately available and the rates of extraction of these resources. Applying this criterion to the assessment of waste management provides the explanation of the benefits from waste management process. The abiotic resources which are saves due to material and energy recovery from waste are considered as benefits in this indicator.

  - **Climate Change**

    Climate change is regarded as the impact of the emissions on the atmosphere which causes the earth surface temperature to rise. This can consequently cause adverse impacts on ecosystem, public health and material welfare. Typical emissions for the treatment of waste that effect to climate change potential consist of CO_2, N_2O and methane (den Boer et al., 2005) which are mainly emitted by transportation, treatment and disposal of waste.

- **Human Toxicity**

  Human toxicity is the assessment criterion which is concerned with the adverse effects on public health. Application of this criterion within waste management can demonstrate the negative impact of inappropriate waste management to human health. Emissions, from waste management, which have the most significant impact to human toxicity consist of heavy metals, dioxins, barium and antimony (den Boer et al., 2005 and Hellweg, 2003).

- **Photo-oxidant Formation**

  This criterion refers to the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants (den Boer et al., 2005). These reactive compounds can cause the negative effects to public health and ecology. Relevent emissions, from waste management, which effect to the photo-oxidant formation category are non-methae volatile organic compounds and methane from landfills, and the emissions of NOx and CO from waste thermal treatment (den Boer et al., 2005 and Hellweg, 2003).

- **Acidification**

  Pollutions with high acidity (either originally acid or converted to acid by processes in environment) have the significant impacts on surface waters, groundwater, soil, organisms and built environment. Within waste management, typical emissions that have significant impacts within this category include NO from thermal processes, NH_3 from biological processes and SO from electricity production (den Boer et al., 2005 and Hellweg, 2003).

- **Eutrophication**.

  This impact category covers all potential impacts of excessively macronutrients which mainly focus on nitrogen (N) and phosphorus (P). Excessively enrichment of nutrient can cause some negative impacts on ecosystem such as surplus production of biomass in aquatic ecosystems resulting in high BOD value and unsuitable water quality. Hence, in this category, BOD is regarded as eutrophication impact potential which is the result from the emissions of biodegradable matter. As for waste management, the impacts within this category arise from N and P emissions from biological processes.

The general targets of waste management according to the EU waste policy are also set as criteria which show below (See Appendix II for details).

- **Packaging Recovery and Recycling Targets**

  Packaging waste includes plastics with all compositions, glass and metals generated by households. It excludes waste electrical and electronic equipment (WEEE) and bulky waste. The processes making this kind of waste become usable consist of recycling and recovery. The total amount of recycled packaging waste includes sum of each single packaging component in the output of sorting facilities. While the total amount of recovered packaging waste includes the sum of mentioned recycled packaging waste including with the sum of packaging entering the incineration or the cement kiln. The recycling and recovery rates are calculated by relating to the amount of packaging waste generation. These recycling and recovery rates can be used for comparing to the directives of EU waste policy in order to demonstrate the efficiency of defined waste management scenario. More details provide in Appendix II.

- **Targets for diversion of organic waste fraction from landfilling**.

  The target and directive on landfill of waste based on European waste policy aims to reduce the biodegradable MSW that directly goes to landfill by the year of 2016 by reaching a reduction to 35% of biodegradable waste going to landfill in 1995. Compliance with this landfill directive target will provide the result showing how efficient of the defined waste management scenario.

- **Environmental sustainability assessment**

The environmental sustainability assessment is concerned with the pollution emissions and resources consumption throughout the system. The environmental assessment, as same as the other assessment, starts at the moment waste is put in a temporary storage system (see details in the background modules). Apart from waste streams, the flows of products from the processing of waste, such as recovered materials, recyclables, compost and recovered energy are also considered in the assessment. These products are regarded as a credits or positive effect.

According to the concepts of Life Cycle Analysis (LCA) that use as a boundary for making an assessment, the inventory analysis is applied for the assessment. Inventory analysis covers the calculation of inputs (in terms of raw materials and energy) and outputs (in terms of emissions to air, water and solid waste) for each stage. By multiplying single emissions and resources by characterization factors, they can be attributed to the mentioned six LCA-based criteria. The total characterized values of these six indicators are expressed in inhabitant equivalents (IE). This step, the normalization, enables a comparison between the different indicators. In the Assessment Tool the indicator values are shown for all six LCA-based criteria separately. The description in details for each indicators and the normalization method into inhabitant equivalent (IE) indicator can be found in Appendix I.

2.5.2.2 Economic Assessment

The economic assessment in this LCA-IWM assessment tool provides the economic evaluation of waste management scenario using the principles of economic sustainability. Economic sustainability implies the least expensive waste management system with the adequate incomes to ensure the economically continuous operation which covers aftercare expenses for a period stipulated by law (den Boer et al., 2005).

- **Selection of economic sustainability criteria and indicators**

The main concern of the economic sustainability assessment is the different between costs of solid waste management and income generated by recovered energy and materials. Based on this issue, the Economic Sustainability assessment in the LCA-IWM tool is assessed with the following criteria and indicators:

Economic efficiency:

It is measured by;

- ISWM cost per ton, per household or per person
- Revenue from recovered material and energy
- ISWM cost as % of Gross National Product (GNP) of the city
- Diversion between revenue and expenditures for ISWM system.

Equity:

The goal of using equity as a criterion is to examine the economic burden of ISWM system which is distributed among the citizens. It is measured by;

- ISWM cost per person as % of minimum wage per person; and
- ISWM cost per person/income per person.

Dependence on subsidies:

The purpose of this criterion is to examine whether the ISWM is self sustainable or based on the external financial sources. It is measured by using the Subsidies or grants per person as an indicator.

- **Economic sustainability assessment**

In this assessment tool, all initial capital and operation cost are converted in to equivalent annual costs which can be compared among different scenarios. It is because only initial capital or operation cost of each ISWM subsystem or the whole system cannot identify the efficiency of ISWM system.

2.5.2.3 Social Assessment

Social assessment is not mentioned in our research due to the complexity of the input. However, the social assessment in the LCA-IWM assessment tool is shortly mentioned below.

Social sustainability of waste management is regarded as the ethical behavior of a waste management system towards society (den Boer et al., 2005). This means in particular that the management of municipal waste responsibly towards society is not just accomplishing legislation. Accomplishing the acceptances of the society is very significant.

- **Selection of social criteria**

Three different perspectives are considered in the social assessment section of the LCA-IWM assessment tool:

- Social acceptability
- Social equity
- Social function (social benefit of ISWM).

- **Social sustainability assessment**

Each indicator will be marked. This mark is the result of the combination of several quantitative and qualitative variables. Hence, a score between 0 and 1 is achieved for each indicator. The user of the LCA-IWM assessment tool is allowed to aggregate all indicators by a weighting step.

CHAPTER 3: METHODOLOGY

The main objective of this research is to evaluate the effectiveness of the application of waste-to-energy technology for community-scale integrated solid waste management (ISWM). The goal of this research is to demonstrate the benefits that the community can gain from WtE ISWM system which includes environmental, public health, economic and energy recovery aspects. The objective of this research can be divided into three parts as the steps for achieving the goal of the project.

- To estimate waste breakdown for the community level by demonstrating the case study model of community-scale waste generation.
- To identify the most suitable integrated solid waste management (ISWM) system for the modelled case which includes separation method, treatment and WtE facilities, and disposal method. The proposed system should be sustainable and provides economic and environmental profit to the community.
- To identify environmental and economic benefits provided by the proposed system to the community.

3.1 Research Design

In order to achieve these above objectives, the research design was divided into two sections. The first section is to develop the case-study model of the small community in order to estimate the waste generation rate from this case-study model. The waste generation model studied by Beigl et al. (2004) is adopted to use as a tool for the estimation.

The second section will provide the modelling of Integrated Solid Waste Management (ISWM) system for the community-scale model which includes all stages since waste storage, collection, transportation, treatment until disposal. Four different scenarios are developed that can demonstrate which is the most efficient application of ISWM for community level. For the assessment section, the LCA-IWM assessment tools developed by Den Boer et al. (2005) which have been mentioned in the literature review section is adopted to use for making an assessment on environmental and economic impacts. The diagram of overall research design is shown in Figure 7.

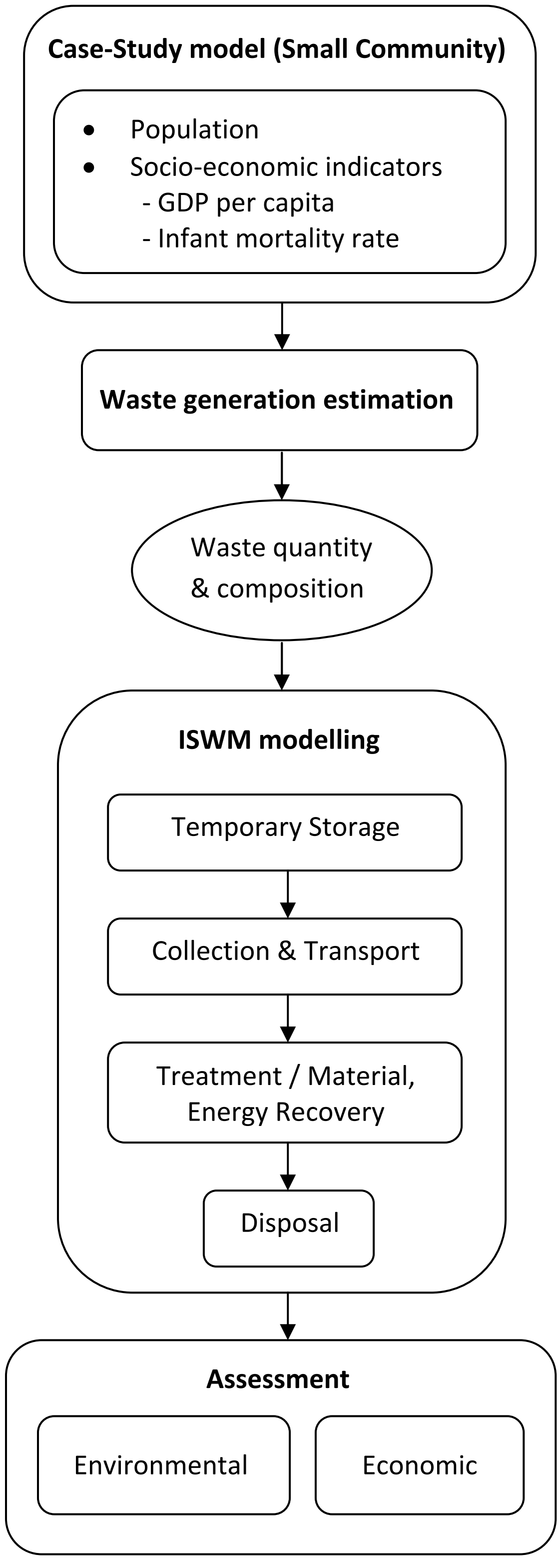

Figure 7: Research Design Diagram

3.2 Modelling of Case-study ISWM System

3.2.1 Waste Generation Estimation

The estimation of waste generation rate in this section is using the model based on the study of Beigl et al. (2004). As mentioned in the literature review section that the waste generation model developed by Beigl et al. (2004) is related to the influence of the socio-demographic characteristics of the studied location. Table 5 show the significant socio-economic factors that regarded as the significant influence on this waste generation.

Table 5: Influencing Factors as Model Parameters on MSW Generation

Factor	Unit
Gross domestic product per capita[a]	USD PPP[b] at 1995 prices
Infant mortality rate	Per 1,000 births
Population aged 15 to 59 years	Percentage of total population
Household size	Persons per household
Life expectancy at birth	Years
Labour force in agriculture	Percentage of total labour force

1 Only the national indicator is significant in these cases.

2 American Dollar Purchasing Power Parities

Source: den Boer et al., 2005

3.2.1.1 Waste Generation rate

The result from the study by Beigl et al. (2004) mentioned that the waste generation rate per capita is different between the prosperity levels of the city and have the relationships with the above mentioned socio-economic indicators as be shown as the set of formulas (see 2.2.2 for details).

In our paper, the MSW generation model of very high prosperity level will be adopted because the study would like to focus on the community-scale waste management that can be reflect as an example for UK community. Note that UK is regarded as a country in the very high prosperity level according to socio-economic indicators (Beigl et al., 2004). Thus very high prosperity model of Beigl et al. (2004) is be the best example that can demonstrate waste generation rate of the European country with high economic rating. The formula of waste generation rate in the very high prosperity model is,

$$MSW^t = 359.5 + 0.014 \times GDP^t - 197.1 \times \log\left(INF_{urb}^t\right)$$

Where;

- GDP^t is the national gross domestic product per capita at 1995 purchasing power parities,
- INF is the infant mortality rate per 1,000 births in the city (INF_{urb})
- GDP per capita is assumed to be 21,000 USD at 1995 purchasing power parities which can reflect as the suitable GDP value for the community with very high prosperity level such as that in UK.
- INF is assumed to be 5 per 1,000 births which can reflect as the suitable infant mortality rate value for the community with very high prosperity level such as that in UK.

The result for MSW generation model with this assumption provides the estimated MSW generation rate as 516 kg/capita/year.

In order to make the model suitable as an example for community level, the number of population for this model is assumed to be 50,000 inhabitants. Hence, the total MSW generation in this considered community-scale model is 25,790 tons per year.

3.2.1.2 Waste Composition

In this study the MSW composition generated from our community-scale case study model is estimated by using the historic data collected from the European country. Table 6 shows the types of waste which have been considered in this model.

Table 6: Considered Types of Generated Municipal Solid Waste

Material-related groups	Considered waste types
Recyclables	Paper and Cardboard
	Glass
	Metals
	Plastics and Composites
Organic waste	Biowaste
	Garden Waste
Other materials	Mixed[1] or Residual[2] waste
	Bulky waste

1 Mixed waste is understood as similar as household waste collected in municipality where no separate collection scheme is implemented.

2 Residual waste consists of those wastes which remain for collection after source separation of recyclables

Source: den Boer et al., 2005

Based on the prosperity classification of the cities using to estimate waste generation rate, it is also important to identify the relationships between prosperity level of the city and the waste potentials of each MSW fractions. The data of 31 European cities in different years which have been evaluated by Beigl et al. (2003) is adopted to use as an assumption in our model.

Figure 8 shows very significant differences of the potential of paper and cardboards in the four groups. An increasing prosperity level leads to higher potentials of this fraction. The paper waste potential rises from 18 up to 24 percent in the highest group.

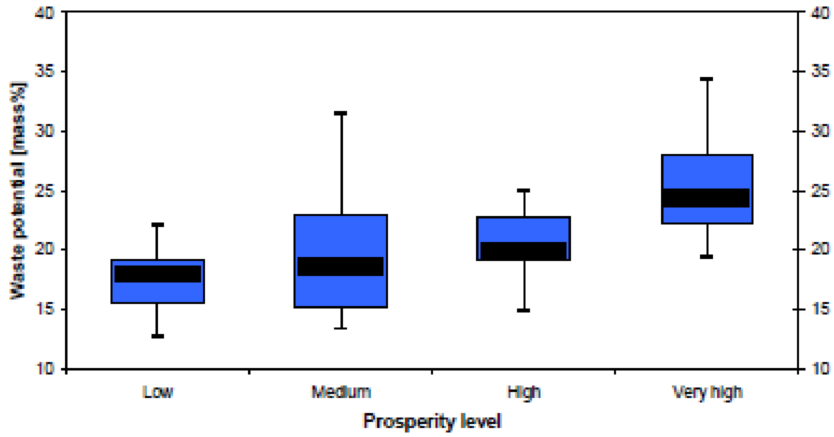

Figure 8: Prosperity and waste potentials in cities – Paper and cardboard (mass-%)

Source: Beigl et al., 2003

For organic waste fraction, considering the mass percentages of MSW generation versus prosperity level shows that there is a obvious significant decrease from 45 mass% in the low prosperity level group to the two wealthiest level groups (33 respectively 34 mass %) (Figure 9).

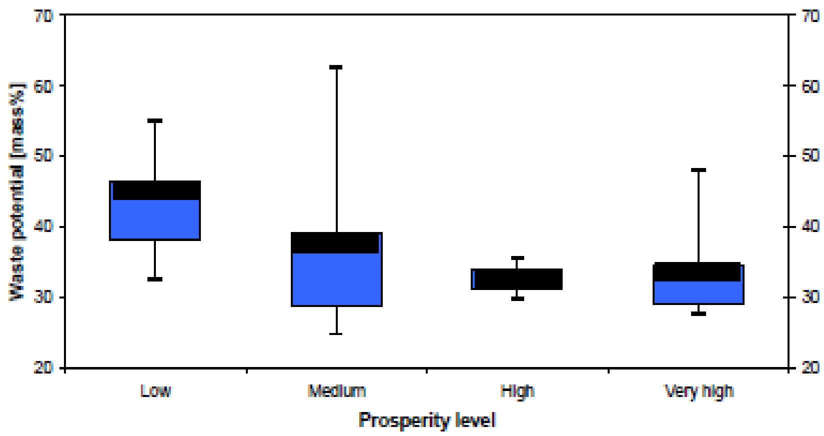

Figure 9: Prosperity and waste potentials in cities – Organic waste (mass-%)

Source: Beigl et al., 2003

Concerning the other recyclables, there are no such significant trends of the waste potentials which go hand in hand with social and economic development. Figure 10 shows the glass potentials with no apparent relationship to the stage of development. The differences are potentially due to regionally different consumption patterns (e.g. low glass and high plastics consumption in some Polish and Greek cities in the second group).

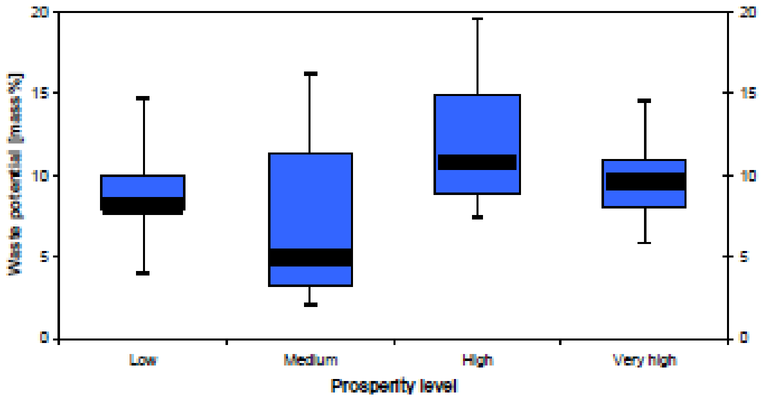

Figure 10: Prosperity and waste potentials in cities – Glass (mass-%)

Source: Beigl et al., 2003

Figure 11 shows mass percentage of plastics and composites which equals to 10%–15% of total MSW generation for around two thirds of the cities. Much lower values were obtained for cities with a low income as well as from results of sorting analyses in Polish cities from the early 1990s. These findings are linked to the later introduction of plastics as the main packaging material in these cities.

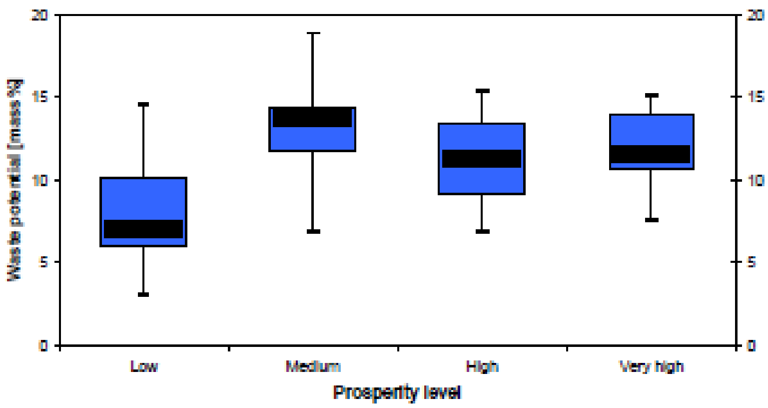

Figure 11: Prosperity and waste potentials in cities –

Plastics and Composites (mass-%)

Source: Beigl et al., 2003

Concerning metal waste potentials, Figure 12 shows that the median values of the four groups are within the narrow range between 3.7 and 4 mass percent.

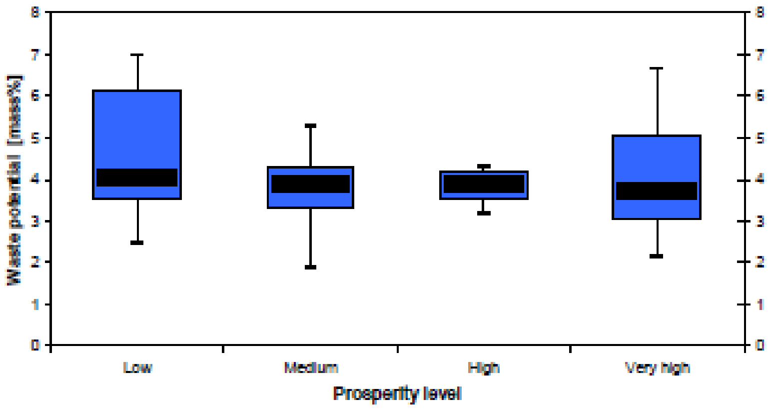

Figure 12: Prosperity and waste potentials in cities – Metal (mass-%)

Source: Beigl et al., 2003

As mentioned in this paper that relationships of waste characteristics in the very high prosperity community is concerned in order to develop the ISWM model. Therefore, the historic data of waste composition in European country that show relationship between waste composition and prosperity level is used as an assumption for the estimation of waste composition in our case-study model. Table 7 and Figure 13 show the assumed data of waste composition in our case-study model.

Table 7: Assumption of MSW Composition in the ISWM Model

MSW Fraction	% mass
Paper, Cardboard	24
glass	9
plastics and compounds	12
organic waste	33
Metals	4
Others	18

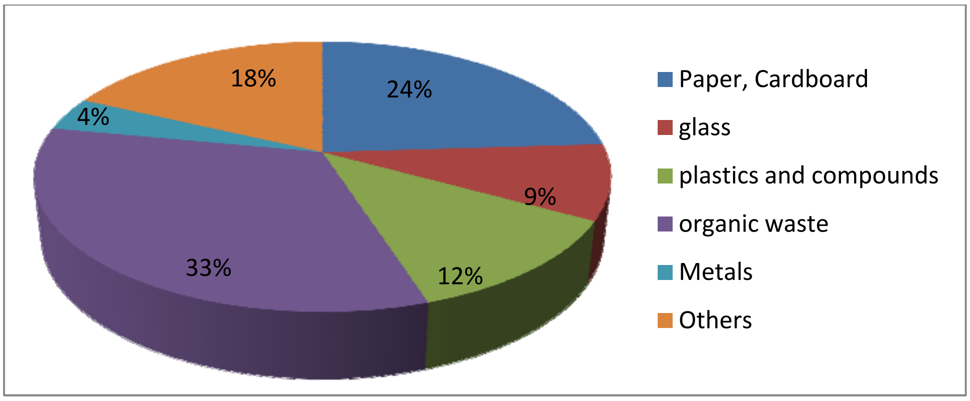

Figure 13: Assumption of MSW Composition

Therefore, the summary of our case-study model in term of the estimated amount of MSW generation by fractions is shown in Table 8.

Table 8: Summary of Case-study ISWM Model for Community Level

MSW Fraction	**Amount (t/y)**
Paper, Cardboard	6,190
Glass	2,321
Plastics and Compounds	3,095
Organic waste	8,511
Metals	1,032
Others	4,642
Total	***25,790***

Note: Assumed population in the community – 50,000 inhabitants
Estimated MSW generation rate – 516 kg/capita/year

3.2.2 ISWM Model

The modelling of Integrated Solid Waste Management (ISWM) for our community case-study model that mentioned earlier in the research design is developed based on the concept of the study: *The Use of life Cycle Assessment Tools for the Development of Integrated Waste Management Strategies for Cities and Regions with Rapid Growing Economies* (TU Darmstadt, URV Tarragona, BOKU Vienna and others, 2005). In the assessment part of this ISWM model, the idea of Life Cycle Analysis (LCA) will be applied to use. Hence, the process such as temporary storage, collection and transport are included in this ISWM modelling. Figure 14 shows the diagram of our community-scale ISWM modelling.

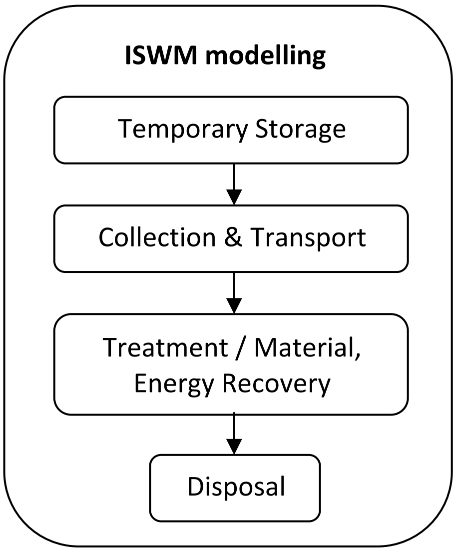

Figure 14: ISWM modelling diagram

In this section the details of each stage are introduced in order to describe how the ISWM case-study model is developed.

3.2.2.1 Separate Collection Performance

Separate collection performance means the separation and collection of MSW at source. (See Figure 15) Separate collection by waste compositions plays an important role as a factor for the modelling of the ISWM system.

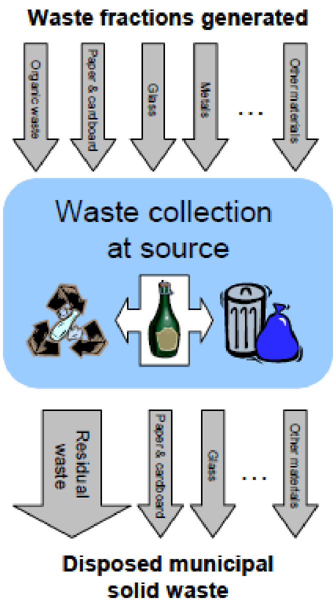

Figure 15: Separated Collection of MSW

Source: Beigl et al. 2003

In our case-study ISWM modelling, the separate collection performance is included as one of the factor that influences to the model assessment. It uses as the indicator that can demonstrate the efficiency of the purposed ISWM system in source-separated performance aspect.

The investigation of separate waste collection performance in European cities that has been analysed by Beigl et al (2003) is used as our assumption. It has been assumed in the study of Beigl et al (2003) that experiences about the development of collection rates in the mature collection systems, such as in Germany or Austria, can be transferred to developing collection systems with actually low rates of separately collected fractions.

The results from the mentioned European investigation shows that the source-separated collection rates in the cities clearly depend on the general socio-economic status. The same four prosperity level as the estimation of waste generation rate has been also defined for this case.

It has been assumed that the average value of collection rates of all cities in the wealthiest prosperity group (this group contains cities in Germany, France, Ireland, United Kingdom, Italy and Netherlands) should serve as target value for the remaining cities which should be achieved within 10 years after implementation of a separate collection scheme. Alternatively the achievement of the highest percentile in this group should serve as optimum value. (Beigl et al., 2003)

The mentioned target and optimum values are shown in table 9.

Table 9: Recommended Target and Optimum Values for Separated Collection

Waste fraction	Recommended rates of separate collection			
	Target value		Optimum value	
	mass%	kg/cap/yr	mass%	kg/cap/yr
Paper and Cardboard	45	50	74	90
Glass	50	22	69	40
Plastics and composites	33	19	65	30
Bio-bin collected organics	22	35	51	82

In our community-scale ISWM modelling, the optimum value for separated collection is set as the target value to be achieved. Therefore, the percentage of separated collected waste stream from the generation source is assumed to be equal to this optimum value. For an example, the amount of separated collected waste stream of the modelling of Scenario 1 (The details of all modelling scenarios in this research will be described in the Results and Discussion section) is shown in Figure 16 and Table 10

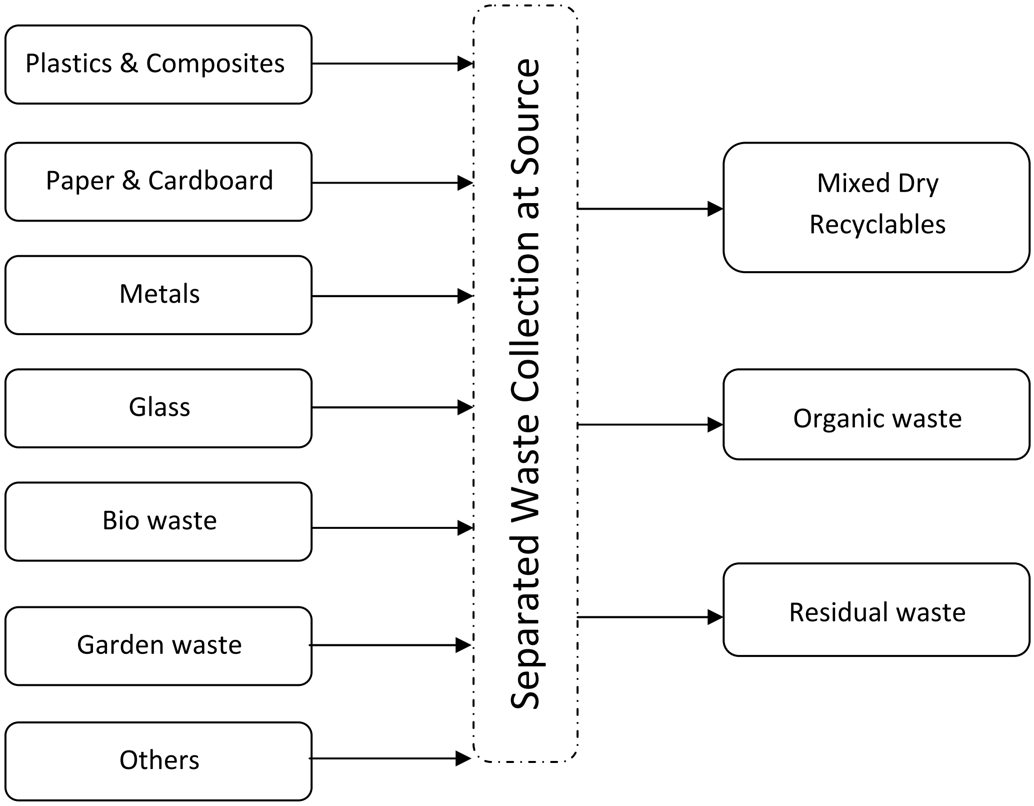

Figure 16 Separated collection performance of designed ISWM model

Table 10 Separated collection performance of designed ISWM model

MSW by collected waste streams		**Generated amount (tons/year)**		**Optimum value for separated collection (%)**	**Collected amount (tons/year)**
Mixed Dry Recyclables (MDR)	Paper & Cardboard	6,190	12,638	69	8,720
	Glass	2,321			
	Plastics	3,095			
	Metals	1,032			
Organic waste	Bio waste (70%)	5,957	8,511	51	4,342
	Garden waste (30%)	2,553			
Residual waste (other material, non-separated waste)		4,642			12,730*

* note that non-separated collected MDR and organic waste are included in the collected residual waste.

3.2.2.2 Temporary Storage

The temporary storage scheme of the ISWM modelling in this research is designed based on the LCA-IWM assessment tool as mentioned in the literature review section. In the LCA-IWM assessment tool, the input is based on the source separated waste streams which have been estimated based on the optimum target value which shows in Table 9. Output is the different waste streams that are stored in sacks, bins or containers. Type and dimension of bins and sacks are defined including with the collection frequency and average filling rate of bins in order to estimate the number of bins and sacks in the community. Table 11 shows the designed temporary separated scheme in the ISWM modelling in this research which has been assumed based on the study by Cardiff Council (2007).

Table 11 Assumed value for temporary storage scheme

MSW by collected waste streams	Bins or Sacks (litres)	Collection frequency (times / year)	Cost
Mixed Dry Recyclables (paper, cardboard, glass, plastics, metals)	Bin* – 240 l	52	£18 / 1bin
	Sack* – 60 l	52	£20/100 sacks
Organic waste (bio waste, garden waste)	Bin – 240 l	52	£18 / 1bin
Residual waste (other material, non-separated waste)	Bin – 240 l	52	£18 / 1bin

* Assumed that 70% of inhabitants using 60 litres sack, and the other 30% using 240 litres bin

3.2.2.3 Collection and Transport

Collection and transport scheme of the ISWM model in this research is designed based on the LCA-IWM assessment tool as well as the temporary storage section. As mentioned in the literature review part that the collection and transport includes collection of non-separated and separated solid waste and recyclables in a studied area and the transportation of the collected waste and recyclables to processing and disposal facilities. Transportation after collection of MSW can be divided into two cases which includes; Collection and reloading at a transfer station prior to transport and Collection and direct transport to the facility or landfill. In this research the second case is applied to use because our study focus to the community-scale ISWM which the generated MSW is less than the necessity of using transfer station.

The data required for designing this collection and transport scheme includes;

- Transport distance
    - Average distance from the garage to the first pick-up in a defined area *– in this case the value is 0 because the garage assumes to be in the studied area.*
    - Average distance from the sector to the designated facility

Table 12 shows the assumed value for transport distance of the collection and transport scheme in the ISWM model in this research.

Table 12 Assumed value for temporary collection and transport scheme - Transport distance

Main category	Sub category	Value	Note
Transport Distance	Avg. distance from the garage to the first pick-up	0 km [a]	garage assumes to be in the studied area
	Avg. distance from studied area to transfer station	0 km [b]	no transfer station
	Avg. distance from studied area to facility	4 km	

- Vehicle types and performance characteristics
  - Type of vehicle; it includes type of vehicle that use for short bin-to-bin waste collection in the studied area and type of vehicle that use for transporting to the waste treatment facility – *in this research, there is no transfer station designed in the model so the transportation vehicle is not need.*
  - Loading capacity; it includes design capacity by vehicle which is the maximum permissible mass of load on a defined vehicle (in tons).
  - Fuel consumption: it includes average Diesel consumption (litres per 100 km), average Diesel consumption while loading (litres per hour)

Table 13 shows the designed Vehicle types and performance characteristics in this model.

Table 13 Assumed data for temporary collection and transport scheme - Vehicle types and performance characteristics*

Vehicle type	Capacity	Fuel Consumption	Performance
Typical standard vehicle for bin-to-bin collection: approximate maximum weight of 20 tons	*7 tons*	- while running: ***27 litres/100km*** - while loading: ***1 litres/hour*** - between pick-up : ***6 litres/hour***	• Avg. time per used vehicle: ***220 days/year*** and ***7 hours/day*** • Avg. speed between transfer station and facility: **50 km/hour** • Avg. time spent for loading: - Per loaded collection sack with 10 kg waste: **0.1 minutes** - Per loaded bin with less than 500 litres: **0.5 minutes**

* These data obtained from LCA IWM assessment tool default value

3.2.2.4 Treatment

In this study, the MSW treatment system that is used for modelling is shown as a diagram in the Figure 17. The implementation of treatment facilities is different among each scenario. The details for each scenario will be mentioned in the results and discussions part. The estimated waste streams which are separated collected and transport to this treatment facility of different scenarios are also shown in the Figure 22-25 in the results and discussions part. The amount of estimated waste streams has been mentioned in the separated collection performance section.

The technologies selected for modelling in the treatment scheme are the ones most commonly used in modern waste management system in Europe adopted from the study by den Boer et al. (2005). They are considered as state-of-the-art, but already broadly verified treatment methods.

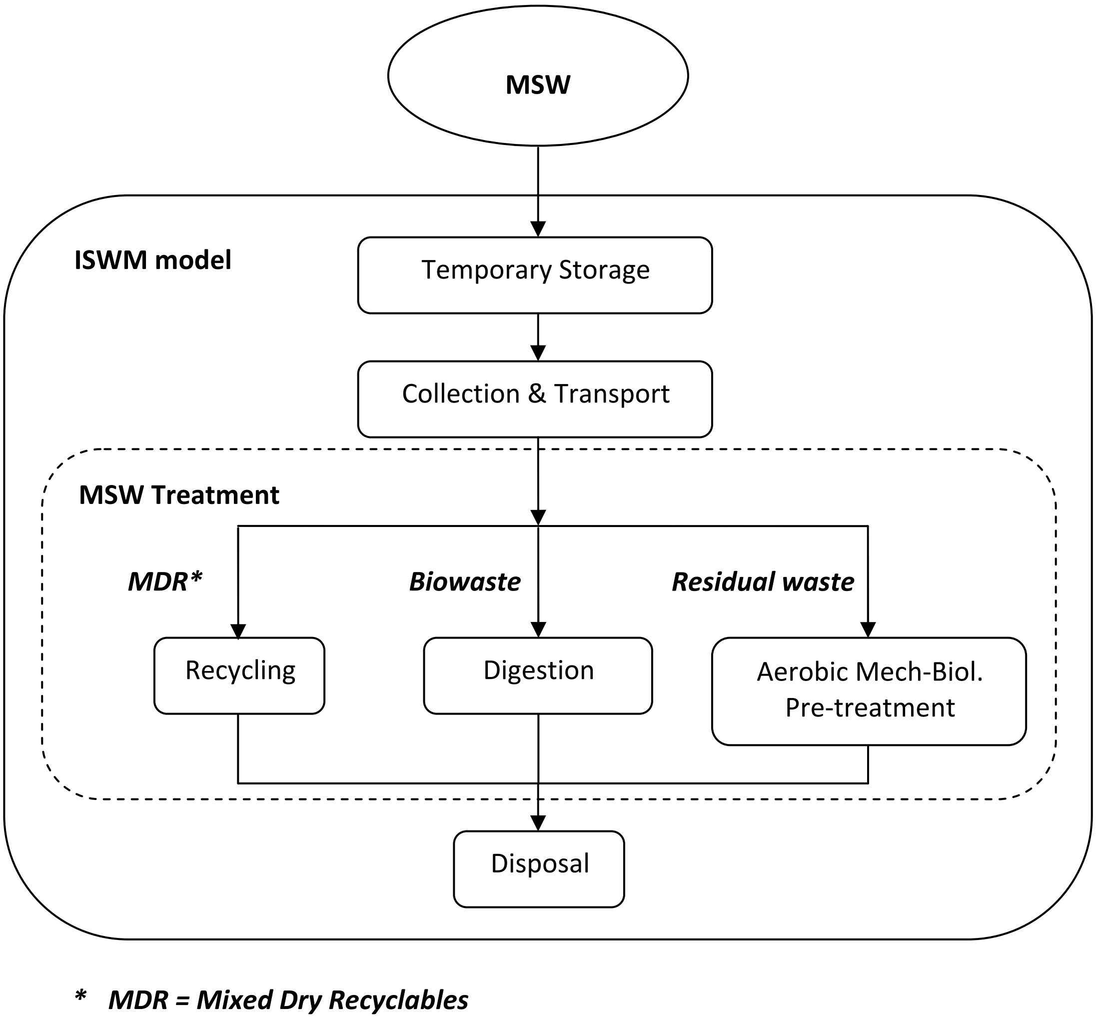

Figure 17 MSW Treatment Scheme of the Designed ISWM Model

Anaerobic Digestion

In this project only the mono-digestion of separately collected biowaste, eventually combined with garden waste is considered. The term biowaste is used as a generic term for both biowaste and garden waste which will be used to describe in this section.

Digestion processes can be divided into wet or dry, thermophilic or mesophilic and 1-stage or 2-stage processes. For this project a thermophilic dry 1-stage process has been modelled. This is the most common process type for the digestion of biowaste in Germany (den Boer et al., 2005 based on Fricke et al. 2002, Kern 1999, and Vogt et al. 2002).

Although materials of good structure, like garden waste mostly is, are principally more suitable for a composting, they can be digested as well, especially in dry digestion processes. In the digestion module both biowaste and garden waste are allowed waste inputs. If however the total input tends to be of good structure material (wood like, celluloses) composting is the preferable treatment option.

Prior to digestion, the separately collected biowaste undergoes a mechanical pretreatment, in which contaminants are sorted out. In the actual digestion phase biogas, wastewater and a digestion residue are produced. The biogas is combusted in an engine to produce electricity and heat. The residue is further treated in the aerobic maturation process stage, producing compost. Waste water is treated in a waste water treatment plant (WWTP). The produced compost as well as the sludge from the WWTP is applied on agricultural land.

In Figure 18, an overview diagram of anaerobic digestion plant that is used in this study can be seen.

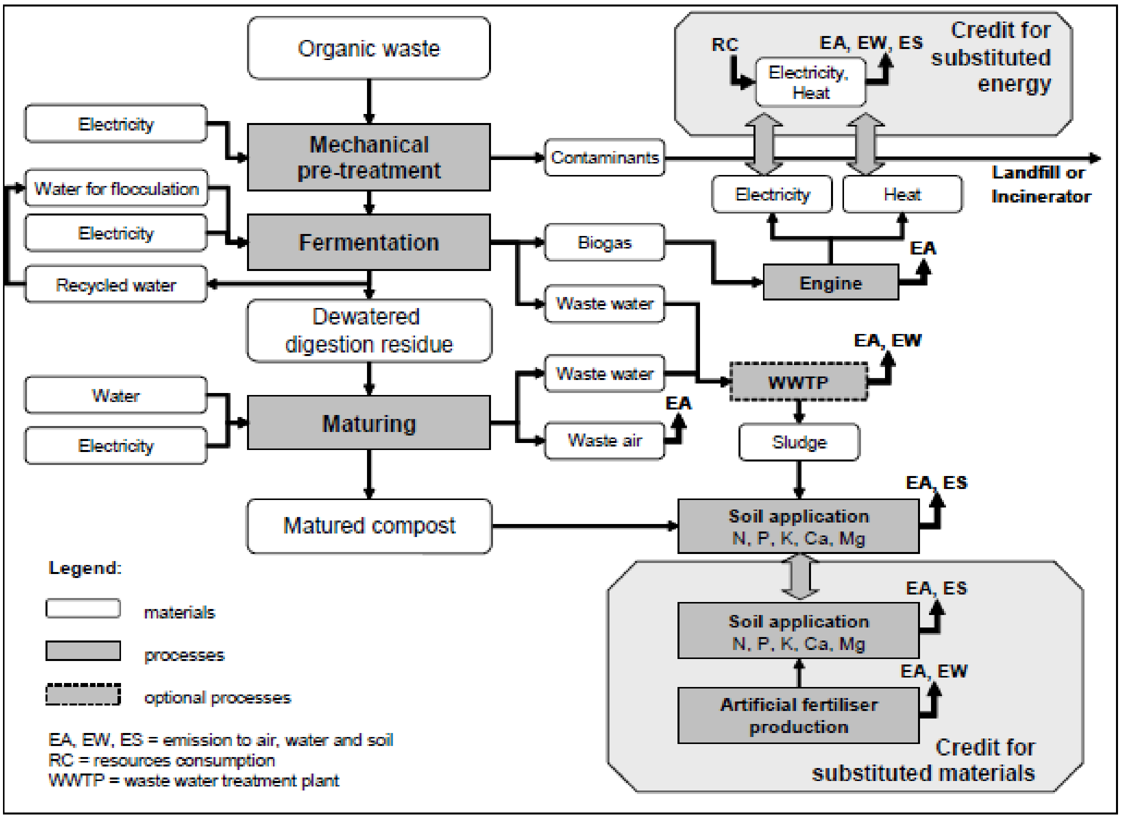

Figure 18: Main Material Flows in the Modeled Anaerobic Digestion System

Source: den Boer et al., 2005

In the actual digestion, or fermentation process, the substrate is heated up to thermophilic conditions (50-60 °C) (den Boer et al. 2005 based on Fricke et al. 2002). The biogas yield has a major impact on the overall assessment of the digestion process. For this model a value of 0.38 m3/kg of organic dry matter (ODM) is taken (Vogt et al. 2002) which provide the biogas yield accounts to 141 m3/t of biowaste input.

In this model the energy production in a combined heat and power (CHP) system is defined. In the CHP unit, the biogas is combusted and producing both electricity and heat. It is assumed, that heat utilization has no influence on the electrical efficiency of the engine (den Boer et al. 2005 based on Vogt et. al. 2002). Table 14 shows the estimated output from the designed digestion plant based on our assumption.

Table 14 Estimated output from Anaerobic Digestion facility

Process	Content	Amount	Unit	Note
Input	Organic Waste input	4,342	t/y	45% Dry matter Organic DM = 87% DM
Mechanical Pre-treatment	Contaminants	217	t/y	
	Water Recycling	2,475	m^3/y	
Fermentation	Biogas	612,222	m^3/y	
	Waste Water	1,910	m^3/y	
	Water for flocculation	999	m^3/y	
	Dewatered digestion residue	2,436	t/y	45% Dry matter
Engine	Electricity	772,876	kWh/y	
	Heat	1,697,722	kWh/y	
Composting	Compost	1533	t/y	60% Dry matter

Water emissions in the digestion plant mainly occur in the fermentation phase. Heavy metals and nutrients partly leach out to the water effluent and partly remain in the digestion residue and thus in the compost (in the maturation phase there is no leaching of metals or nutrients other than N assumed). The total emissions from this AD process as shown in Figure 18 is determined and accounted to the environmental assessment in the LCA-IWM assessment tool.

In the maturation process the digestion residue is treated further (aerobically) in order to produce marketable compost. The maturation stage requires on average 4 weeks of post rotting in windrows in a rotting hall. After this period compost reaches the rotting grade of IV-V, which is typical for mature composts. The flue air resulting from maturation is emitted diffuse.

For the initial capital investment and operating cost, the estimation is conducted based on the suggested cost curve for anaerobic digestion treatment in the LCA-IWM assessment tool which has been mentioned in the literature review section (2.2.2) and Appendix I. Table 15 shows the capital investment and cost estimation in this model case. The assumption of revenues from selling products – i.e. electricity and compost – is provided in Table 16.

Table 15: Initial capital investment and operating cost estimation of defined AD facility

Category	Estimated values	Note
Design Capacity	4,342 ton/year	
Initial Capital Investment of facility	£ 2,830,000	20-year horizontal analysis for economic assessment with closure cost of facility at year 20 equals to £ 141,500
Annual operation and maintenance cost	£ 90/ton	

Table 16: Assumption of revenues from selling products

Products	Assumed values	Note
Electricity	4p/kWh[a]	No selling of recovered heat from the facility
Compost	£5/ton[b]	

a Based on ROCs ((West Wales ECO Center, 2009))

b Based on Market Report on the Composting and Anaerobic Digestion Sectors (Inter Trade Irland, 2009)

Aerobic Mechanical-Biological Pre-treatment of waste

Mechanical-biological pre-treatment (MBP) is a method alternative to the incineration of pre-treatment of mixed or residual waste prior to landfilling. The MBP of municipal solid waste has been applied since about 10 years, especially in Germany, Austria and Switzerland. In Germany about 1,8 million tons out of 35 million tons of municipal solid waste are treated in 29 MPB plants (Soyez and Plickert 2001).

The aim of MBP is to minimize the environmental impacts of landfilling and to gain value from waste through metals and energy recovery. The main MBP technology on either splitting or stabilization approach.

- In the splitting approach, first mechanical division of waste takes place and a derived fraction of material is treated biologically.
- In the stabilisation approach, the entire waste is subject to biological treatment with subsequent splitting of the mass fractions for recycling and refuses derived fuel (RDF).

The selected MBP technology in this study is aerobic MBP with fully encapsulated and consists of mechanical pretreatment with separation of the high caloric light fraction and biological treatment of the remaining waste prior to landfilling. The described technology is based on results of a joint study on the performance of MBP plants in Germany (Soyez et al. 2000).

The biological process is conducted in an aerated windrow with a weekly turning of the material. Within this option intensive rotting and aerobic stabilisation takes place in the same windrow. The aeration rate is controlled automatically by the temperature in the windrow. This ensures conduction of an intensive rotting in first three weeks and gradually lower process intensity in the following weeks. Assuming optimal process conditions a far reaching stabilisation of the low caloric fraction is achieved within 14 – 16 weeks. In optimal case the first stage, in which the main part of the decomposition takes place (app. 80% of total decomposition) can be achieved in ca. 4 – 6 weeks (Müller 2001). Further material stabilisation is achieved in the stabilisation stage, which normally takes 6 to 10 additional weeks. The end product of these processes stabilized low calorific fraction – can be landfilled or used for recultivation of degraded land. The high calorific fraction after refining can be used as a Refuse Derived Fuel (RDF) in a cement kiln or in an incineration plant.

The estimated material flows from the designed aerobic MBP plant based on the assumption are shown in Table 17.

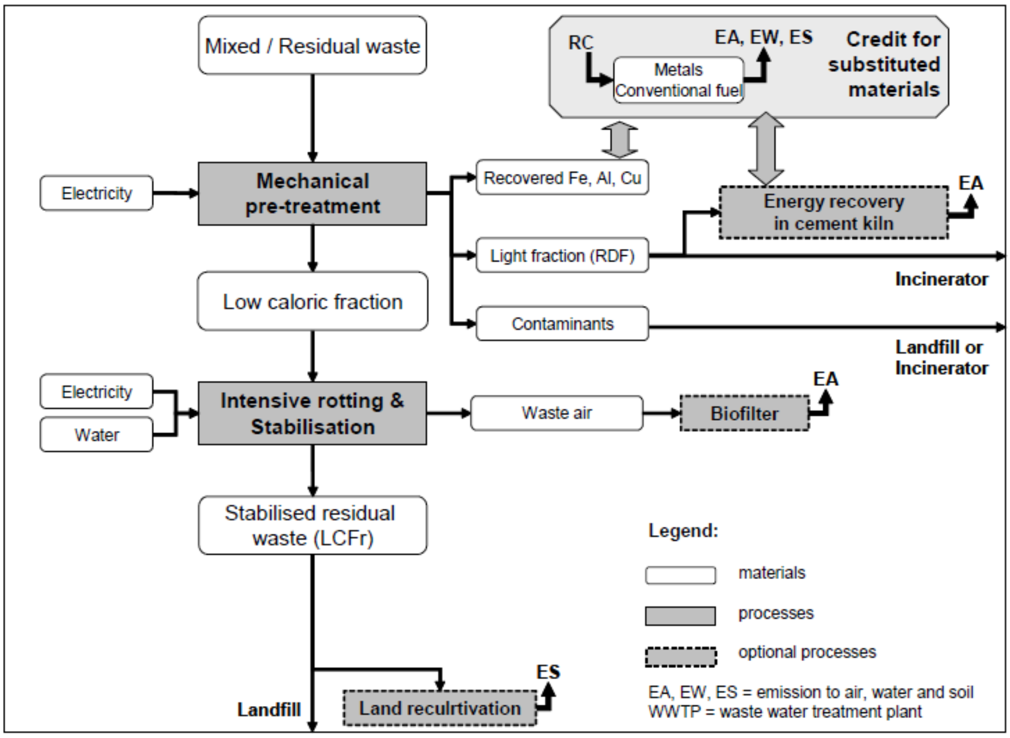

Figure 19: Main Material Flows in the Modeled Aerobic MBP System

Source: den Boer et al., 2005

Table 17 Material flows from the aerobic MBP facility

Process	Content	Amount	Unit	Note
Input	Residual Waste input	12,731	t/y	65% Dry matter Organic DM = 47% DM
Mechanical Pre-treatment	Fe	293	t/y	
	Al	13	t/y	
	RDF	1,553	t/y	17.6 KJ/kg RDF
	Contaminants (to landfill)	789	t/y	
Intensive rotting and Stabilisation	Stabilised waste for landfilling	5,831	t/y	
Energy Consumption	Electricity	700,205	kWh/y	
	Diesel	6,366	litres/y	

For the initial capital investment and operating cost, the estimation is conducted based on the suggested cost curve for aerobic MBP system in the LCA-IWM assessment tool which has been mentioned in the literature review section (2.2.2) and Appendix I. Table 18 shows the capital investment and cost estimation in this model case. The assumption of revenues from selling products – i.e. Metals (Fe and Al) – is provided in Table 19.

Table 18: Initial capital investment and operating cost estimation of defined aerobic MBP facility

Category	Estimated values	Note
Design Capacity	12,731 ton/year	
Initial Capital Investment of facility	£ 2,360,000	20-year horizontal analysis for economic assessment with closure cost of facility at year 20 equals to £ 118,000
Annual operation and maintenance cost	£74/ton	

Table 19: Assumption of revenues from selling products

Products	Assumed values	Note
Fe	£140/ton[a]	No selling of RDF
Al	£410/ton[a]	

[a] Based on the default value from LCA-IWA assessment tool

Waste Recycling

Waste recycling part in this ISWM model is designed based on the Waste Recycling module in the LCA-IWM assessment tool which allows calculating for all of these waste fractions - paper & cardboard, glass, metals, plastics and compounds - in order to provide the result in benefits or negative impacts of these recycling processes. In the LCA-IWM assessment tool, the LCIs (life cycle inventories) such as fractions composition, contaminants presence in fractions and their destination, transport distances, electricity origin at a country level, operation conditions of Materials Recovery Facilities (MRF) are used as an input in the module for estimating the environmental and economic impact.

In our designed model, the recyclable waste stream enters the recycling module is defined as the mix dry recyclables (MDR). It is assumed that MDR compose of fourteen major sub-fractions which are shown in Table 20. Mix dry recyclables (MDR) are sort in the MDR sorting which is a semi-mechanised Material Recovery Facility (MRF). It includes the following separation operations:

1. bag opening (mechanical ripping unit),
2. films separation (air separation),
3. tinplate steel separation (magnet separator),
4. aluminium separation (eddy current separator),
5. liquid beverage cartons separation (near infrared and air separation) and
6. Plastics sorting (manually).

Then, the different sub-fractions are transported to their corresponding recycling facilities. Rejects of sorting processes and the sub-fraction “other composites” are landfilled.

Table 20 shows the designed recycling process of waste recycling in this ISWM model which based on the study in the LCA-IWM tool.

Table 20 Recycle process designed in the model

Mixed Dry Recyclables (MDR) by fraction	Composition (mass %)	Recycling Process
Paper and Cardboards	- Paper of de-inking quality - 60 - Cardboard - 35 - Contamination - 5	- Paper of de-inking and cardboard are sorted and pre-cleaned in a Material Recovery Facility (MRF) - Paper of de-inking quality is recycled into newspapers. This process consists of repulping and de-inking the incoming paper. - Cardboard is assumed to be recycling into corrugated board. This process consists of re-pulping the incoming cardboard by a combination of testliner and wellenstoff processes - Contaminants are disposed into landfill
Glass	- Mixed glass – 37 - Green glass – 20 - Brown glass – 20 - Clear glass – 20 - Contamination – 3	- Glass is cleaned and crushed into cullet (broken glass) in a Material Recovery Facility (MRF) and transported to a recycling facility. Rejects of cleaning and crushing processes are landfilled - Glass cullet (all colours) is recycled into glass. This process consists of re-melting the incoming cullet in a furnace.

Table 20 Recycle process designed in the model (Cont.1)

Mixed Dry Recyclables (MDR) by fraction	Composition (mass %)	Recycling Process
Metals	- Tinplate steel – 77.5 - Aluminium – 17.5 - Contamination – 5	- Metals are sorted in a MRF and transported to recycling facilities. Rejects of sorting processes are landfilled. - Tinplate steel is recycled into secondary steel by an electrical re-melting process and further metallurgic processes. - Aluminium is recycled into secondary aluminium. This process consists of grinding, decoating and re-melting the incoming aluminium.
Plastic and composites	- HDPE - 13.1 - PET - 15.9 - LDPE film - 16.9 - Mixed plastics - 25.3 - Liquid Beverage Cartons (LBC) - 11.2 - Other - 6.6 - Contaminants - 11	- Plastics and composites are sorted in a MRF as well and transported to recycling facilities - HDPE (all colours) is recycled into HDPE multi-layered bottles. This process consists of grinding, hot cleaning and granulating the incoming HDPE and co-extrusing it with virgin HDPE. - PET is recycled into PET three-layered bottles. This process consists of regenerating by heating the incoming PET and injecting (three-layer) it with virgin PET.

Table 20 Recycle process designed in the model (Cont.2)

Mixed Dry Recyclables (MDR) by fraction	Composition (mass %)	Recycling Process
Plastic and composites	- HDPE - 13.1 - PET - 15.9 - LDPE film - 16.9 - Mixed plastics - 25.3 - Liquid Beverage Cartons (LBC) - 11.2 - Other - 6.6 - Contaminants - 11	- LDPE film is recycled into LDPE sacs. This process consists of cleaning and granulating the incoming film and co-extrusing it with virgin LDPE. - Mixed plastics are recycled into plastic pickets. This process consists of heating and adding calcium carbonate to the incoming mixed plastics and extruding them. - Liquid beverage cartons (LBC) are recycled into pulp for domestic paper. This process consists of re-pulping and de-inking the incoming liquid beverage cartons (recycling of aluminium and polyethylene are not considered).

Source: den Boer et al., 2005

For the initial capital investment and operating cost, the estimation is conducted based on the suggested cost curve for Mixed Dry Recyclable (MDR) sorting in the LCA-IWM assessment tool which has been mentioned in the literature review section (2.2.2) and Appendix I. Table 21 shows the capital investment and cost estimation in this model case. The assumption of revenues from selling recovered material for recycling process is provided in Table 22.

Table 21: Initial capital investment and operating cost estimation of defined MDR sorting facility

Category	Estimated values	Note
Design Capacity	8,270 ton/year	
Initial Capital Investment of facility	£ 2,460,000	20-year horizontal analysis for economic assessment with closure cost of facility at year 20 equals to £ 123,000
Annual operation and maintenance cost	£23/ton	

Table 22: Assumption of revenues from selling recovered material for recycling process

Materials	Assumed values [a]
HDPE (all colours)	£ 41/ton
PET	£ 246/ton
LDPE film	£ 41/ton
Mixed plastics	£ 82/ton
Tinplate steel	£ 140/ton
Aluminium	£ 410/ton
Paper of de-inking quality	£ 25/ton
Cardboard	£ 41/ton
Mixed glass	£ 6.6/ton
Green glass	£ 9.3/ton
Brown glass	£ 9.3/ton
Clear glass	£ 16.4/ton

[a] Based on default value from LCA-IWA assessment tool

3.2.2.5 Final Disposal

Landfilling

The section of landfill in this ISWM model represents a modern landfill which domestic waste and waste similar to domestic is disposed of. Input waste includes raw waste (characterised by material based composition) and mechanically-biologically pre-treated waste. There are two main sources of emissions from the landfill: leachate emissions and the landfill gas emissions. It is assumed that the landfill is equipped with gas and leachate collection systems.

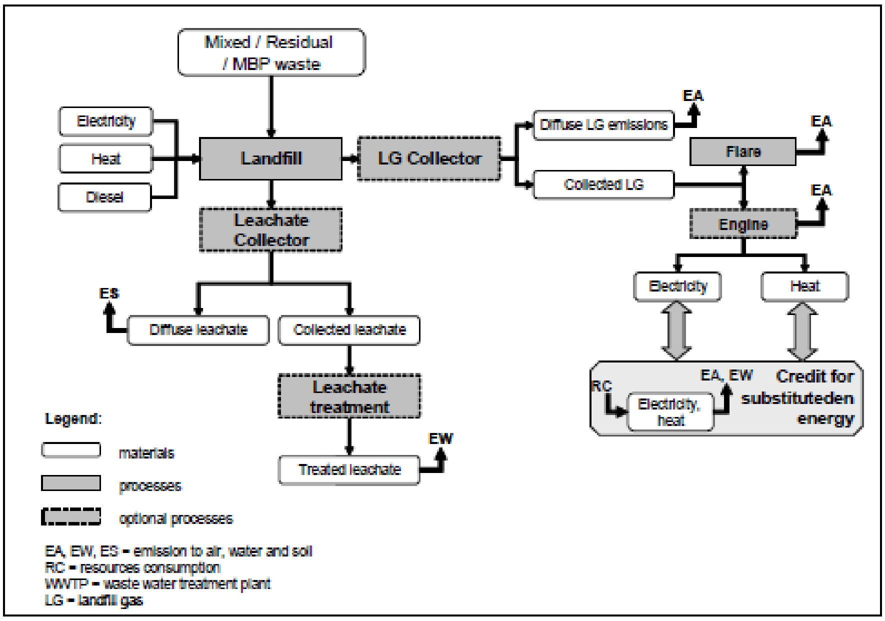

Figure 20: Main Material Flows in the Modeled Landfill

Source: den Boer et al., 2005

3.2.3 Model Summary

As provided in details for each module of the studied ISWM model, Figure 21 can obviously show the overview of this model.

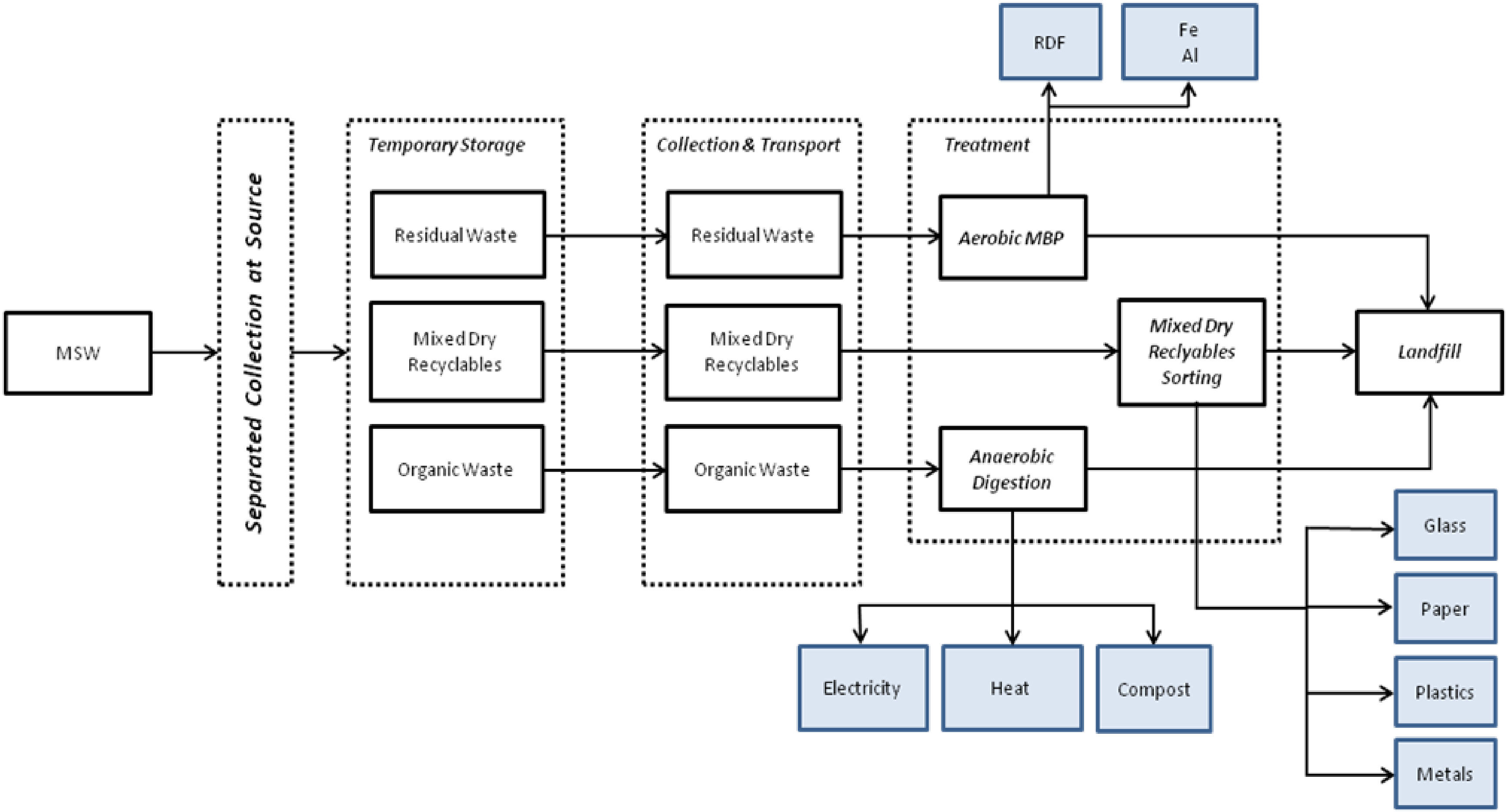

Figure 21: Overview of Designed ISWM Model

CHAPTER 4: RESULTS AND DISCUSSIONS

As be mentioned earlier that the main objective of this research is to find the optimal ISWM among analysed for the small community, there are four different scenarios for the ISWM system modelling in order to demonstrate the different result between each waste management situation. These four scenarios reflect various situations of waste management for the community level. Each scenario provides the possible option of ISWM system which is mainly characterised by the different treatment facilities in the treatment stage, while the other stage, i.e. temporary storage, collection and transportation, are almost remain the same for every scenarios.

The result of the assessment, using the LCA-IWM assessment tool, for each Scenario in the case study model is provided in this section.

4.1 Description of Defined ISWM Model Scenario

4.1.1 Scenario 1

This scenario represents the full integrated solid waste management (ISWM) system with intensified extent which all of waste streams have been treated. Separated collection of organic waste, mixed dry recyclables and residual waste is defined for this scenario. These three waste streams pass the temporary storage, collection and transportation stage through each different treatment options. Organic wastes are treated in the anaerobic digestion system in order to recover energy from biogas generation process. Residual wastes are treated in the aerobic mechanical biological pre-treatment (MBP) system to produce RDF from high calorific fraction and recover some metal, while the rest of residual wastes are stabilised to landfill. And mixed dry recyclables (MDR) are sorted in the MDR sorting facility and delivered each recyclable fraction to each recycling process. Details of each ISWM scheme and treatment option are provided in the ISWM model section (3.2.2).

The overview diagram of Scenario1 is shown in Figure 22.

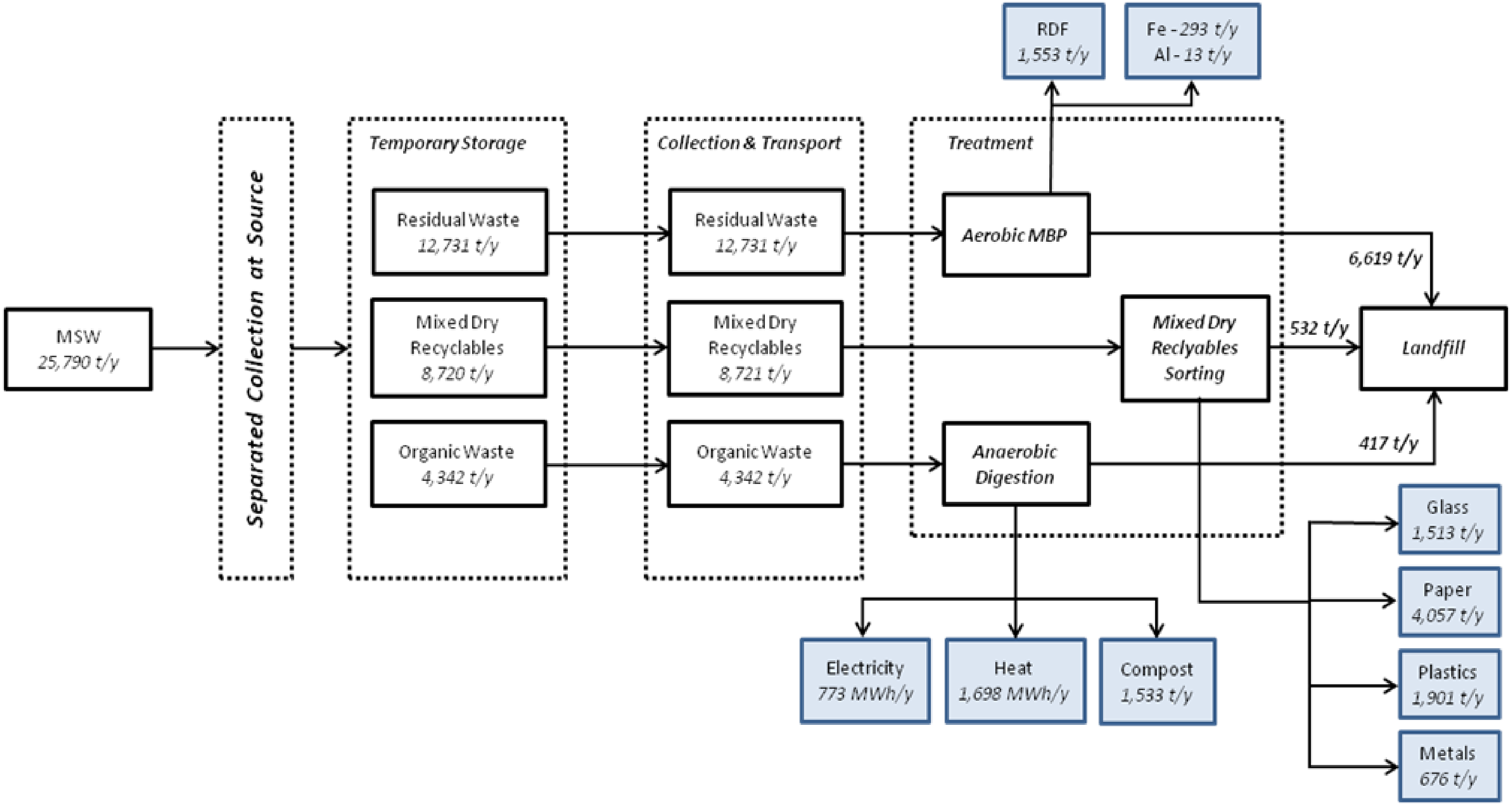

Figure 22: Diagram of Scenario1

4.1.2 Scenario 2

Scenario 2 represents the ISWM system with no treatment option for residual waste is implemented. The rest of ISWM model in this scenario is the same as Scenario 1 since the MSW is separated into three waste streams passing through the same temporary storage and transportation stage. But in the treatment stage, the aerobic MBP is missing in Scenario 2 which results in no treatment for residual waste which passes directly to landfill.

The overview diagram of Scenario 2 is shown in Figure 23.

4.1.3 Scenario 3

Scenario 3 represents the ISWM system which the treatment facility of residual waste and organic waste is missing. There is only recycling process implemented. Separated collection of only two waste streams are defined in this Scenario which consist of mixed dry recyclables (MDR) and residual waste. MDR is sorted and delivered to recycling facility while residual waste is delivered directly to landfill. In this case, organic waste is included in the residual waste which goes directly to landfill, so there is no energy recovery for this Scenario.

The overview diagram of Scenario3 is shown in Figure 24.

4.1.4 Scenario 4

Scenario 4 is set as the opposite case to Scenario 3. It represents the ISWM system which the treatment facility of residual waste and recyclables is missing. There is only AD process implemented. Separated collection of only two waste streams are defined which consist of mixed organic and residual waste. In this case, nixed dry recyclables (MDR) are included in the residual waste.

The overview diagram of Scenario4 is shown in Figure 25.

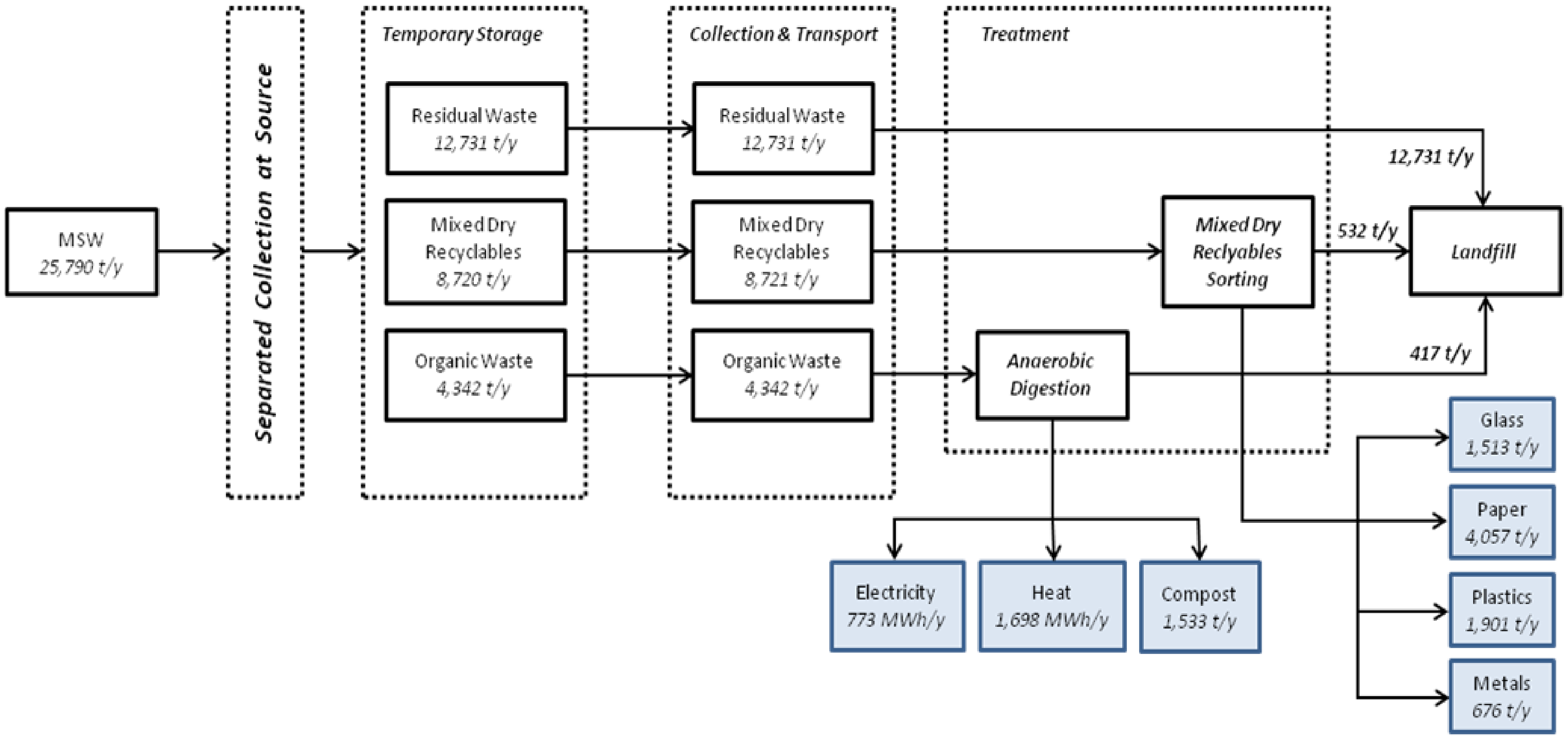

Figure 23: Diagram of Scenario 2

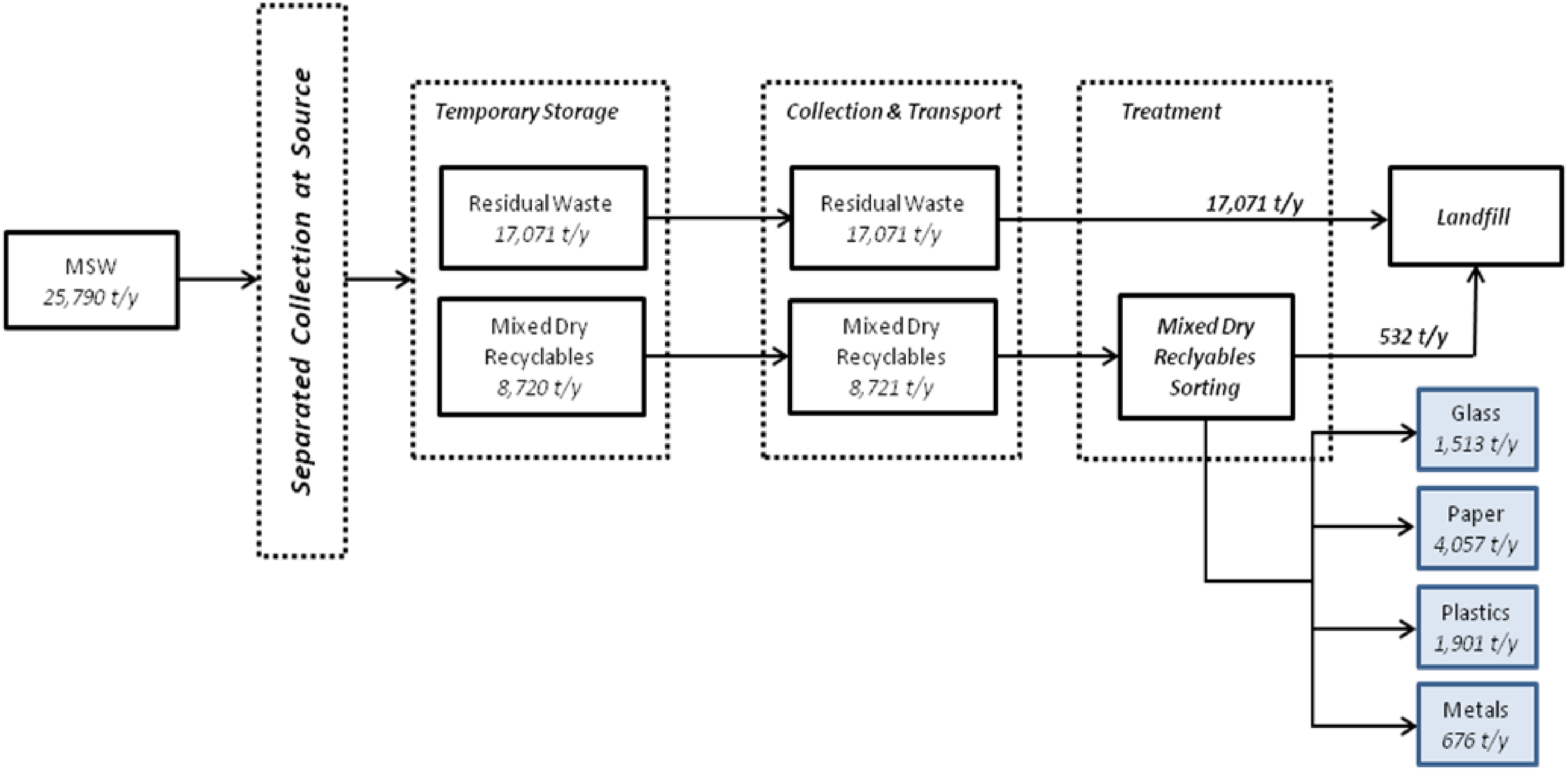

Figure 24: Diagram of Scenario 3

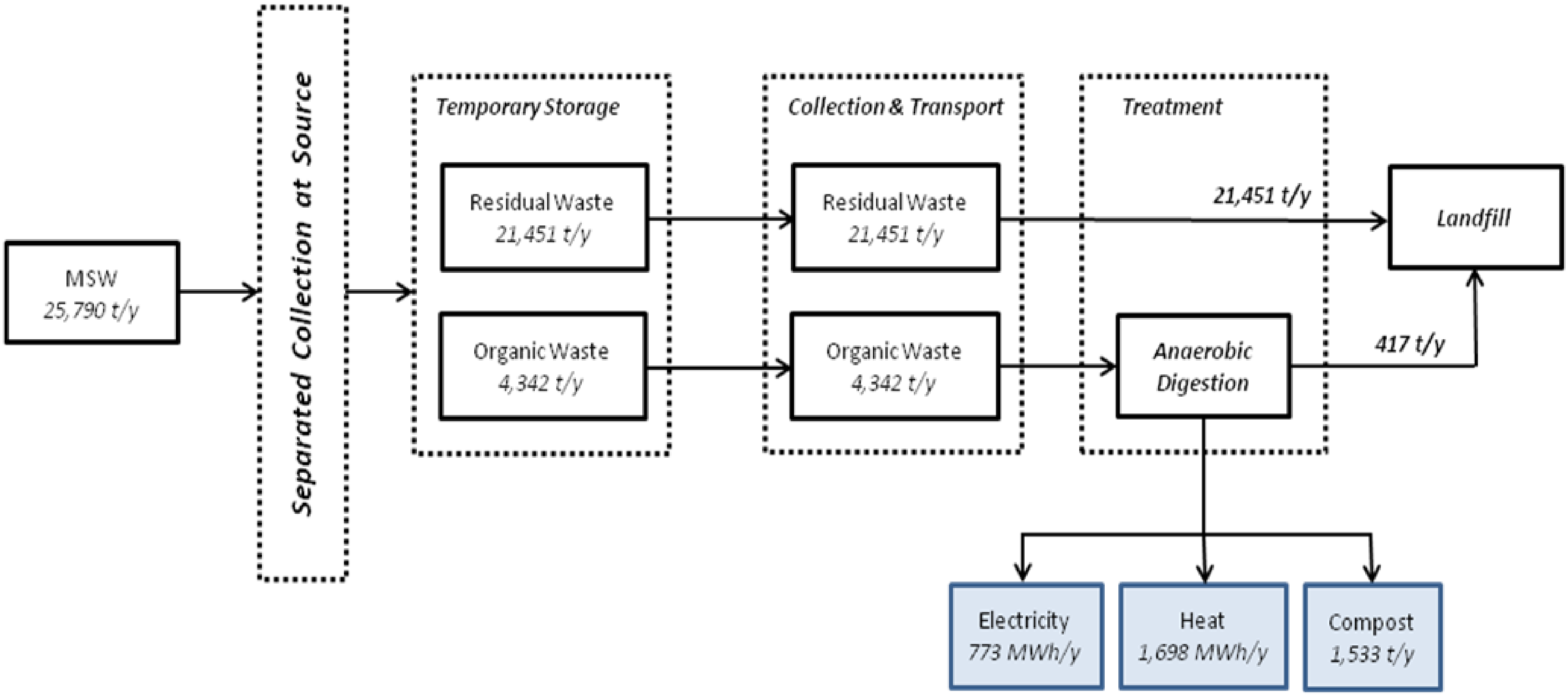

Figure 25: Diagram of Scenario 4

4.2 Output from the usage of LCA-IWM tool – Result of the Modelling

4.2.1 Environmental Assessment

By using the LCA-IWM assessment tool (See section 2.5 and Appendix I for details), the environmental impacts in the unit of Inhabitant Equivalent (IE) separately demonstrating in each impact categories are shown in the form of bar chart below. Note that negative value represents the environmental benefit, while positive value represents the environmental burden. (See section 2.5.2 and Appendix II for details)

4.2.1.1 Environmental Impacts

For all Scenarios, when comparing the environmental impacts of each stage of ISWM, they evidence that the treatment stage has the most influence to gain the environmental advantages (Exception for Scenario 4) in the abiotic depletion, global warming and acidification categories. The other two stages – i.e. Temporary Storage and Collection and Transportation – show the little negative impact (positive IE value) in the abiotic depletion and global warming categories. The calculated values are shown in table 23, while Figure 26-29 obviously represents the results by using bar chart.

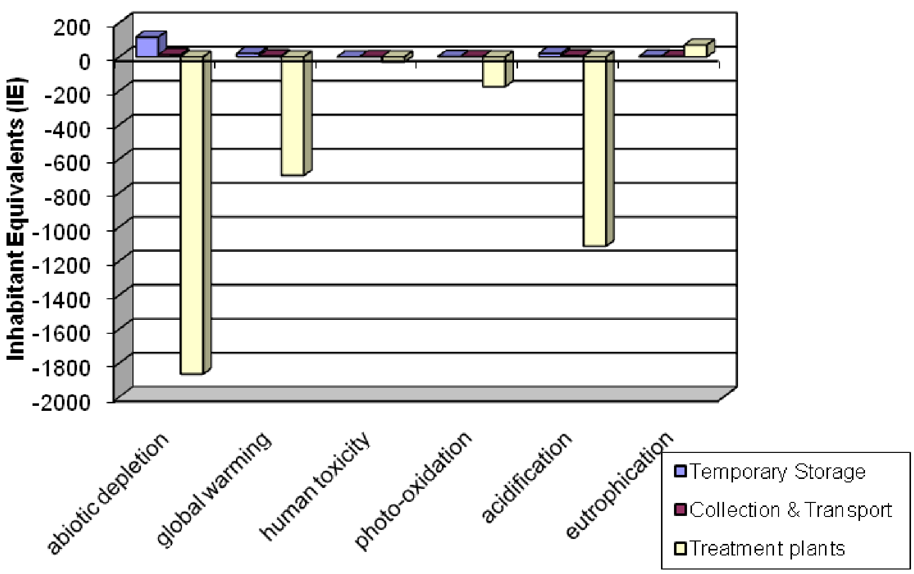

Figure 26: Environmental Impacts for Stages – Scenario 1

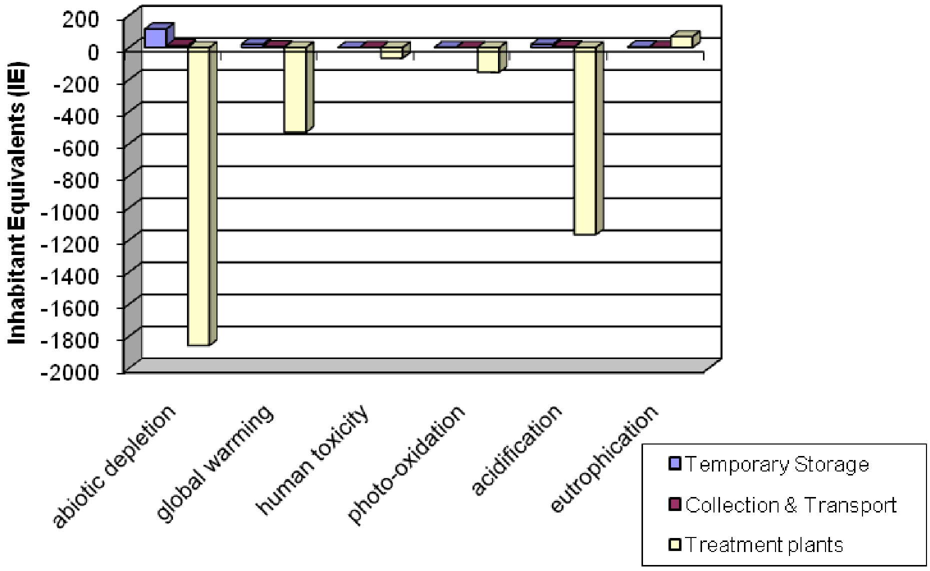

Figure 27: Environmental Impacts for Stages – Scenario 2

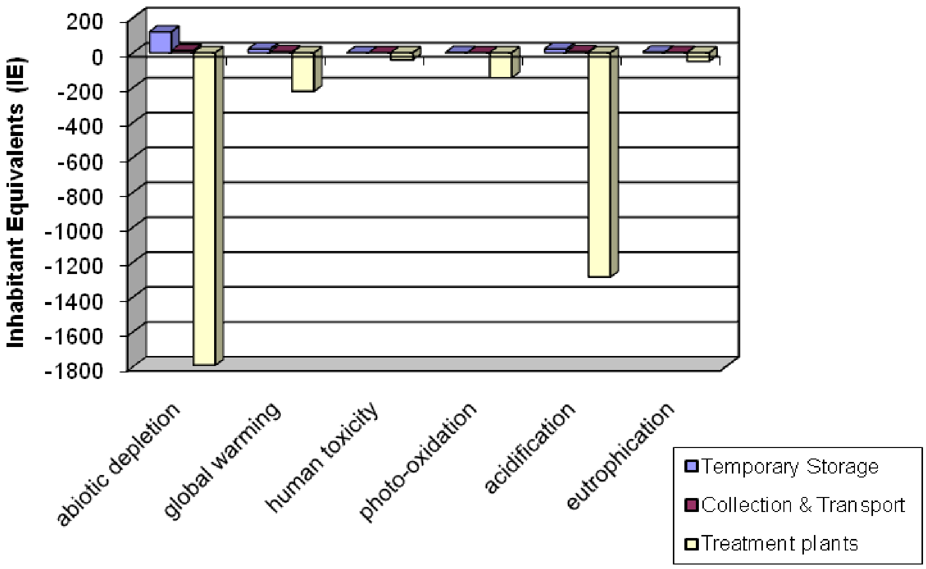

Figure 28: Environmental Impacts for Stages – Scenario 3

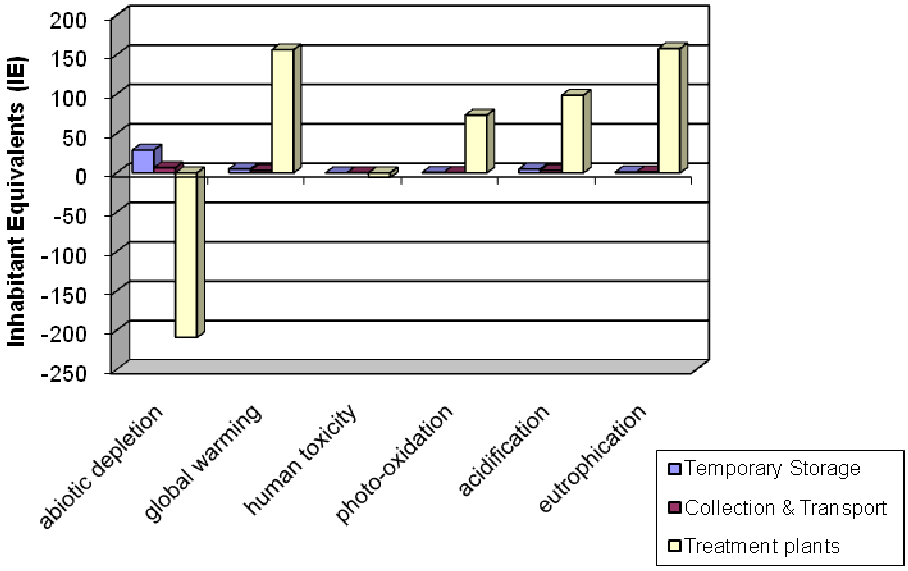

Figure 29: Environmental Impacts for Stages – Scenario 4

The value of environmental impact indicator (in the unit of IE) for each scenario provided in Table 23 shows the different value among each ISWM stage of each Scenario. In case of the temporary storage, collection and transportation stage, the values are not much varying since they are defined as the same situation for every scenario (the same bin and bag size for waste streams, the same transportation distance from community to the facilities for every scenarios). However, note that even though the temporary storage stage in the model is defined as the same for every scenario, the impact can still vary according to the different input waste streams to the ISWM system. For example, in scenario 4, there is no recycling process implemented hence the recyclable waste is combined to the residual waste. According to the model explanation, this residual waste in temporary storage stage is stored in 240-litre bin, while the recyclable waste is stored in sack (See Table 11). The different container in this case can significantly influence the differences in environmental impact that can be seen in Table 23. Similar to the collection and transportation stage, the average distance between communities to each facility which is assumed as an input data for the LCA-IWM assessment tool (See Table 12) can also influence the differences in the impact value of Scenario 4 from the other three Scenarios.

Table 23: Environmental Impact of each ISWM Scenario

Stage	Scenarios			
	1	2	3	4
	Abiotic Depletion (IE)			
Temporary Storage	116	116	119	29
Collection and Transportation	13	13	13	7
Treatment	-1,865	-1,857	-1,791	-209
	Global Warming (IE)			
Temporary Storage	20	20	21	5
Collection and Transportation	6	6	6	3
Treatment	-698	-528	-222	156
	Human Toxicity (IE)			
Temporary Storage	0	0	0	0
Collection and Transportation	0	0	0	0
Treatment	-29	--66	-41	-6
	Photo-oxidation (IE)			
Temporary Storage	2	2	2	1
Collection and Transportation	1	1	1	0
Treatment	-174	-154	-144	73
	Acidification (IE)			
Temporary Storage	20	20	20	5
Collection and Transportation	6	6	6	3
Treatment	-1,113	-1,167	-1,285	99
	Eutrofication (IE)			
Temporary Storage	5	5	5	1
Collection and Transportation	3	3	3	1
Treatment	69	68	-49	158

Therefore, the main consideration is focused on different values of environmental impact on the treatment stage among each scenario which can demonstrate the influences of each treatment option on the environmental aspect. From Table 23, it shows that the differences of the impacts on treatment module among Scenario 1, 2 and 3 are not such a high margin. The environmental impact value is increasing from Scenario 1, 2, and 3 respectively for abiotic depletion and global warming characteristics. This result shows that the lack of aerobic MBP in Scenario 2 and the lack of both aerobic MBP and AD in Scenario 3 cause the adverse impact on these two characteristics (abiotic depletion and global warming) of the environment. However, the huge gap between the environmental impact in Scenario 4 (without MDR sorting) and the others can demonstrate the high influences of recycling process on the impacts to environment

The comparison of the overall environmental impact between each scenario can also prove the significant influence of treatment stage on the impacts to the whole ISWM. Figure 30 obviously demonstrates the trend of impact while changing some treatment option. The environmental impact in Figure 30 is the combined value of the entire stage in the model which consist of Temporary Storage, Collection and Transportation and Treatment as be shown above. The different seen in the Figure 30 is mainly produced by the impact by the Treatment module as mentioned that the other two modules – temporary storage and collection and transportation – are regarded as the same situation.

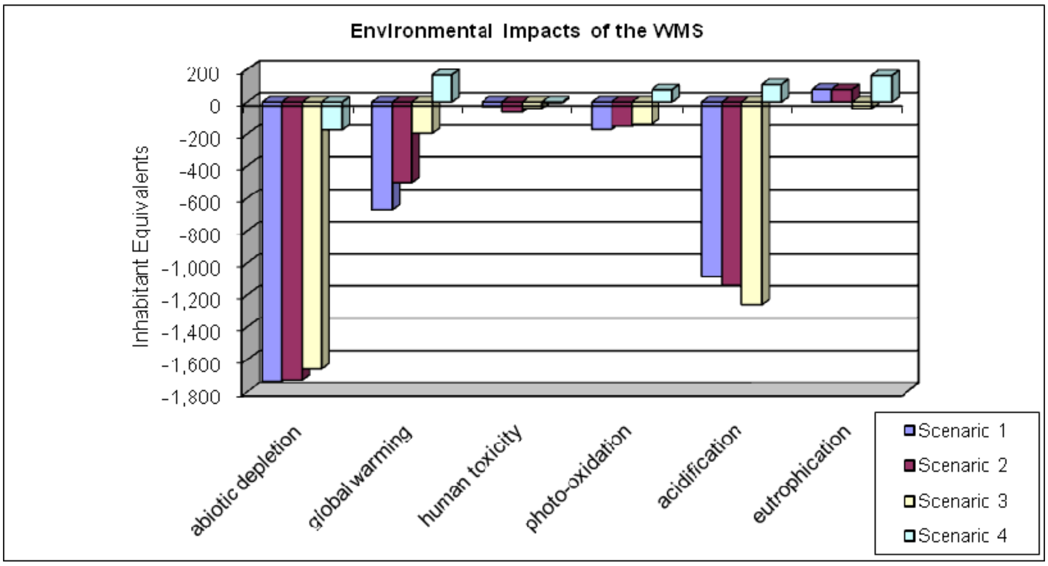

Figure 30: Environmental Impacts of Entire ISWM

For Scenario 1 which is the intensified extent ISWM model, it obviously shows the benefit for all characteristic which mainly contributes to abiotic depletion, global warming and acidification. Environmental relief for adiabatic depletion and global warming is slightly higher than Scenario 2 and Scenario 3 that closely follow respectively.

Scenario 4 – the ISWM model with no recycling process implemented – shows a very clear different behaviour from the others. This result can demonstrate the highly influences of recycling process to the environmental benefit.

4.2.1.2 Recycling and Material Recovery

As mentioned in the section 2.5.2.1 that the general targets of waste management according to the EU waste policy are also set as criteria for the environmental assessment, in this case the packaging recovery and recycling directives based on EU waste policy are used as the target for comparing to each scenario (see Table 3 in Appendix II for details)

Figure 31 obviously demonstrates the mentioned target value comparing to the recycling and recovery ability of each Scenario.

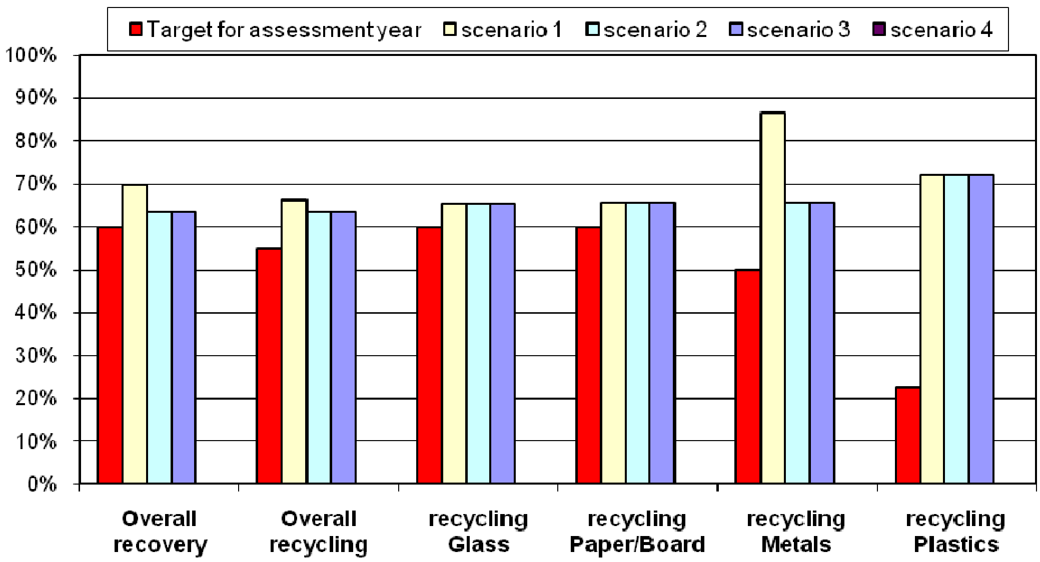

Figure 31: Recycling and Recovery for each Scenario

It can be seen in Figure 31 that all scenarios have achieved targets of packaging directives except Scenario 4. In case of Scenario 4, from the above Figure, there is not any packaging recycling and recovery occurred which is obviously the result from the lack of recycling facility implemented in this Scenario.

Scenario 1 has the highest ability of packaging recycling and recovery which is contributed by the highest metals recycling and recovery. This is the results from the available of aerobic MBP for treating residual waste which is not available in Scenario 2 and 3. Aerobic MBP can recover metal from residual waste from the mechanical pre-treatment process which was mentioned in the section 3.2.2.4. However, the economic assessment should be considered together with this issue because Scenario 1 is the intensified waste management situation which has higher performance along with higher cost than the other Scenarios.

4.2.2 Economic Assessment

By using the LCA-IWM assessment tool for evaluating the economic impacts (See Appendix II for details), the economic impacts are separately demonstrated by each different indicator as been shown in the following Figure and Table.

Firstly, Figure 32 shows the initial capital investment of each scenario, while Table 24 demonstrates the value of the total initial capital investment and the percentage of the annual total cost contributing to each section level. It can be seen in Table 24 that the main annual total cost of the whole ISWM system belongs to the treatment section. Scenario 3 which represent the ISWM system with only MDR sorting implemented has the lowest initial capital cost and the lowest annual total cost of treatment facility. This result is very interesting due to the MDR sorting has been proven as the most significant influences to the environmental benefits of the ISWM system as be mentioned in the environmental assessment. Combining with the relatively low capital cost and the lowest annual cost makes MDR sorting becomes more essential to the ISWM system.

Scenario 1 which is the intensified extent of ISWM system definitely has the highest capital investment. However, comparing to the benefits that can be obtained from environmental benefits including with the significantly higher recovery and recycling ability, this Scenario is still preferable.

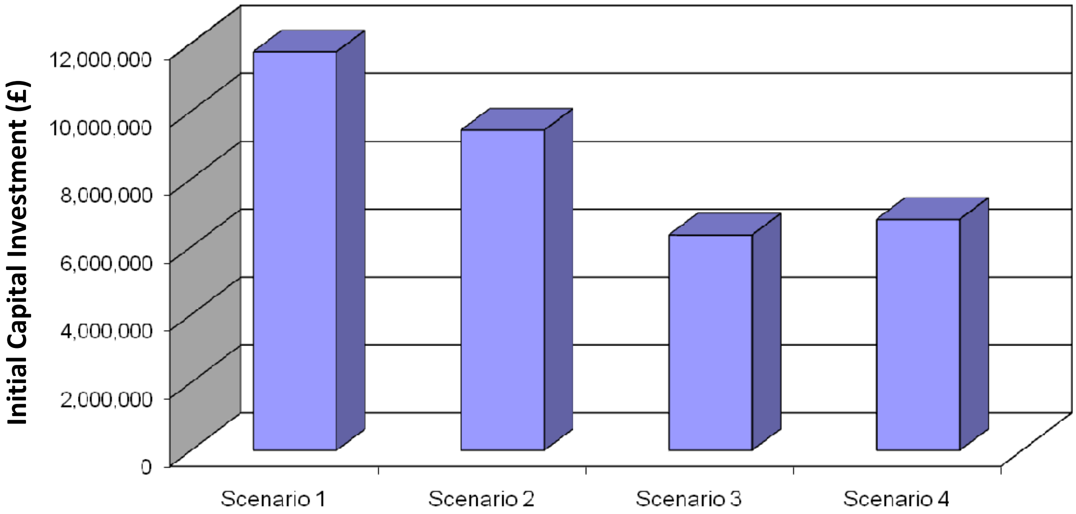

Figure 32: Initial Capital Investment

Table 24: Economic Impact of each ISWM Scenario

Category	**Scenarios**			
	1	**2**	**3**	**4**
Initial Capital Investment (million £)	11.7	9.4	6.3	6.8
Annual Total Cost (£/tons of waste)	143.24	91.42	62.70	53.03
Temporary Storage	14%	21%	32%	4%
Collection and Transportation	8%	12%	18%	13%
Treatment	78%	67%	50%	83%

Table 25 confirms that among three considered treatment facility, MDR sorting is facility with the lowest annual cost. In this table also shows that anaerobic digestion and aerobic MBP have relatively high cost.

Table 25: Economic Efficiency of each ISWM Scenario at the module level

Module	Cost per ton of waste (£/ton)			
	Sc 1	Sc 2	Sc 3	Sc 4
Temporary Storage	20	19.6	19.9	2.3
Collection & Transportation	11	11.3	11.5	7.0
Anaerobic Digestion	183	183	-	183
MDR Sorting	60	60	60	-
Aerobic MBP	111	-	-	-
Landfilling	22	18	16	15

In addition, Table 26 and 27 depicts the economic efficiency of each ISWM scenario. The result in the below table confirms that scenario 1 is the most expensive system. Even scenario can generate more incomes from recovered material and energy but the other indicators are opposite. However, as mentioned earlier that only economic impact cannot demonstrate the efficiency of the system. It should be considered together with environmental impacts and social impact (excluded in this paper).

Table 26: Economic Efficiency of each ISWM Scenario

Indicators	Scenarios			
	1	2	3	4
Cost per ton (£/ton)	143.24	91.42	62.70	53.03
Cost per person (£/person)	73.89	47.16	32.34	27.35
Revenue from recovered material and energy (£)	609,396	568,392	520,051	48,340
Total cost as % of GNP of the city (%)	0.46	0.29	0.20	0.17
Diversion between revenue and expenditure for ISWM (%)	33.84	53.01	77.29	91.41

Table 27: Equity of each ISWM Scenario

Indicators	Scenario			
	Sc 1	Sc 2	Sc 3	Sc 4
Cost per person as % of minimum wage (%)	127.66	81.47	55.88	47.26
Cost per person / income per person (%)	0.23	0.15	0.10	0.09

4.2.3 Summary

Scenario 1 which is the intensified extent of ISWM in community was compared with three possible Scenarios that different ways of treatment are purposed. The comparison of environmental impact of each stage of the ISWM shows that ISWM system in Scenario 1 causes the lowest environmental impact among the other scenarios – in term of global warming and abiotic depletion categories. Scenario 2 and 3 has slightly lower environmental benefits, while Scenario 4 obviously has much lower (more positive value).

Condensed comparison of impacts of all scenarios is shown in Figure 33. The environmental and economic impacts of Scenario 1 are given a value of 100% which the other Scenarios can be compared.

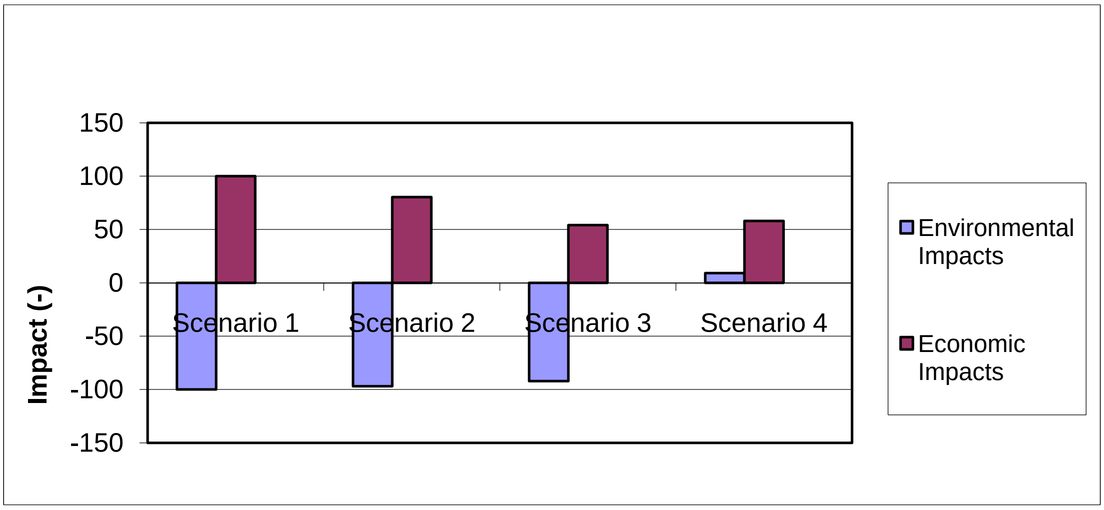

Figure 33: Relative Impacts on Sustainability of the ISWM System

Figure 33 shows that intensified extent of waste treatment leads to overall growing environmental relief – note that: negative impacts represent environmental benefits. It means that benefits from energy recovery of material and energy provide this output. Impact categories of euthrophication, photo-oxidation and human toxicity show relatively small burden of environmental impact between each Scenarios.

However, while taking economic assessment in to account. Investment cost of ISWM model in Scenario1 is bigger than the others. In addition, annual cost of waste management of Scenario is also the highest.

Scenario 1, 2 and 3 achieve targets of packaging directive, while the scenario 4 which has no recycling process implemented cannot achieve.

CHAPTER 5: CONCLUSIONS AND RECCOMMENDATIONS

Four alternative ISWM scenarios reflecting various situations of waste management in the community level were developed for making an analysis. Scenario 1 characterises the most intensified extent of waste management, while the other three analyses the other possible system with less intensified extent which is mainly characterised by different treatment option (Note that: Temporary Storage, Collection and Transportation scheme are almost the same in every Scenario). Obviously, there are also many other potential alternatives in this community level case which not present in this research because this research has the main objective to focus on the ISWM with anaerobic digestion technology as the treatment facility which is the recommended option by the UK government (Defra, 2007). These other potential alternatives could be done using the mentioned LCA-IWM assessment tool during further studies.

Presented results of case-study model show the impacts occurring in each Scenario which differently depend on each stage of the ISWM system. The outputs also demonstrate the level of influences of each ISWM stage to the impacts.

Results of each scenario have shown that proposed ISWM system of all scenarios have provided environmental relief. It has also shown that the more intensified extent system would have provided the more overall benefit to the environment. This is due to the credits allocated to recovery of energy and materials which is contributed mainly by the treatment stage of ISWM (electricity and heat from AD, RDF and recovered metals from aerobic MBP and recycle material from recycling process).

However, improving ISWM system with intensified extent of treatment facilities needs more investments and annual operation costs. Investment and operation costs increase with growing degree of waste management before landfilling. Nevertheless, there is a very interesting result shows that the full MDR sorting and recycling system which have been proved as the facility with highest benefits to the environment entails lower costs than anaerobic digestion and aerobic mechanical–biological pre-treatment of waste (aerobic MBP). This result demonstrates MDR sorting facility as the most important part in the designed ISWM system.

Considering the environmental impact for each treatment option, the most important environmental burden of landfilling is caused by emission of greenhouse gases which is mainly methane from the landfill (This impact by greenhouse gas emission is express by global warming categories). The main environmental burden for aerobic MBP is also in the global warming characteristic, including with the abiotic depletion characteristic. However, as seen the example in scenario 1, this environmental burden by landfilling and aerobic MBP is offset by the overall environmental benefits by the anaerobic digestion and recycling process which have much bigger value than the environmental burden. Figure 34 shows the environmental impact on each treatment option that is used in this research - example from the case of Scenario 1.

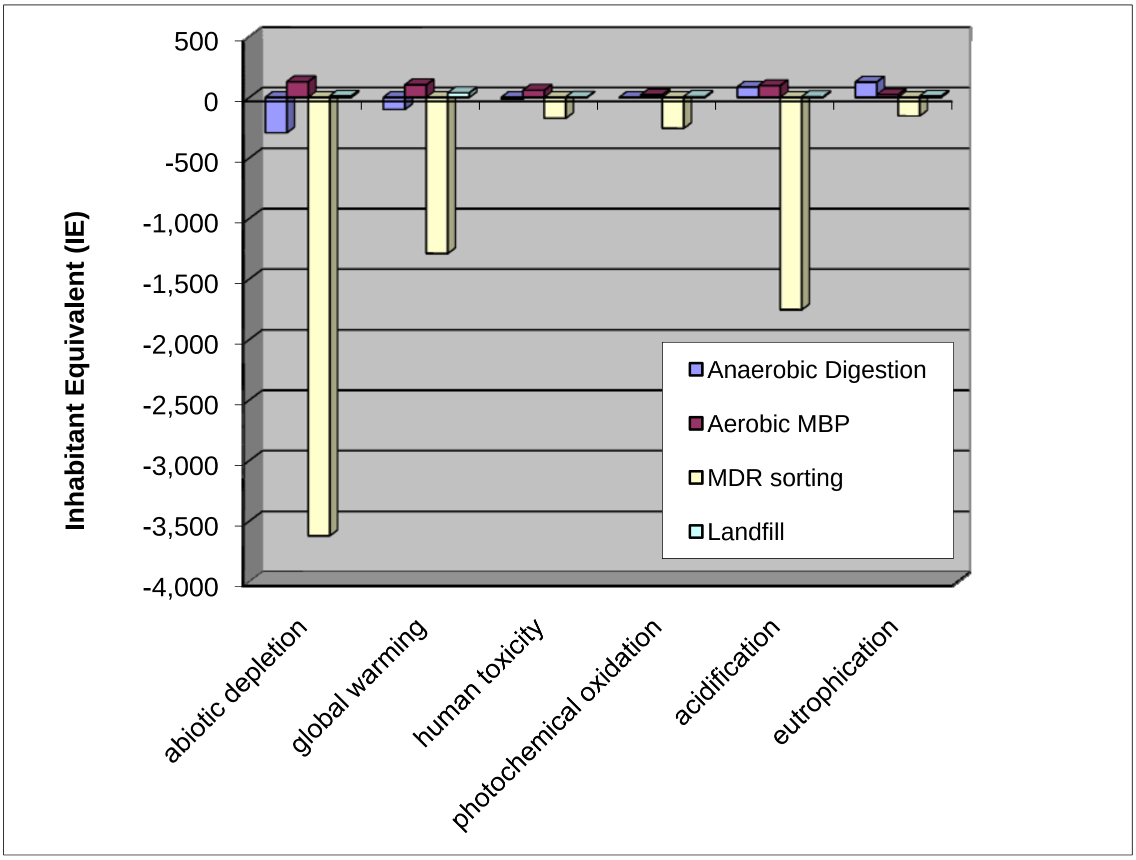

Figure 34: Environmental Impact of Each Treatment Option

From Figure 34, it can be seen that mixed dry recyclables (MDR) sorting for recycling process contributes very high environmental benefits in term of abiotic depletion, global warming and acidification. It contributes benefits much more than anaerobic digestion. This result can obviously show that recycling process is the most significant for the ISWM system in term of environmental benefit. Note that the recycling process considered in this research is regarded as the high efficient process with high separated collection performance (See section 3.2.2.4 for details).

For recycling target, Scenarios 1, 2 and 3 which have MDR sorting facility in the system have been achieved the target based on EU waste policy. This result shows that MDR sorting system is suitable to be included in the ISWM. Other possible recycle system maybe contribute more benefits than MDR sorting, this analysis can be done in the further work.

For economic assessment, it show that the initial capital investment cost as well as annual operation cost increase along with the level of intensified extent of designed ISWM. However, even though Scenario 1 has more investment and operation cost than the other three Scenarios, this cost is still acceptable. As same as the other three Scenarios, the economic impacts of all four Scenarios provided the positive value. This result shows that the community-scale ISWM is also a viable option for implementation according to the economic and environmental impact. The comparison between community-scale and medium to large-scale should be conducted which is not provided in this research due to the limitation of time scale. However, the past paper by den Boer (2005) mentioned that small scale waste management for smaller communities has relatively high unit cost per ton of waste treated but simultaneously has the lower cost per citizens in relation to minimum and average income.

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APPENDICES

Appendix I: The LCA-IWM Assessment Tool – Background Modules

This information is adopted from the handbook of the LCA-IWM assessment tool (den Boer, den Boer, & Jager, 2005) which is developed in the project 'The use of life cycle assessment tools for the development of integrated waste management strategies for cities and regions with rapid growing economies' which is supported by the European Commission under the Fifth Framework Program of energy, environmental and sustainable development (EESD)

Figure 1 gives a general overview of an integrated waste management system including all options for the treatment of waste. These represent the paths the user of the assessment tool may choose for the waste fractions. In the following, each of the depicted background modules is shortly introduced. The calculation methods, background assumptions and applied methodologies of each of the modules are described in detail in the LCA-IWM project deliverables, which are available from the project website.

1. Temporary storage

Temporary storage is the point where the MSW enters ISWM system. Waste is temporary stored in bins, containers and sacks. Figure 2 shows the throughput and the impacts of temporary storage.

The input is based on the source separated waste streams which have been estimated based on the implementation plans. Output is the different waste streams that are stored in sacks, bins or containers. The direct impacts of this stage contain the

- Environmental emissions due to emissions of bin and sack production,
- Total economic costs of this stage as well as
- Social impacts with regard to the social acceptability and social equity of the waste management system.

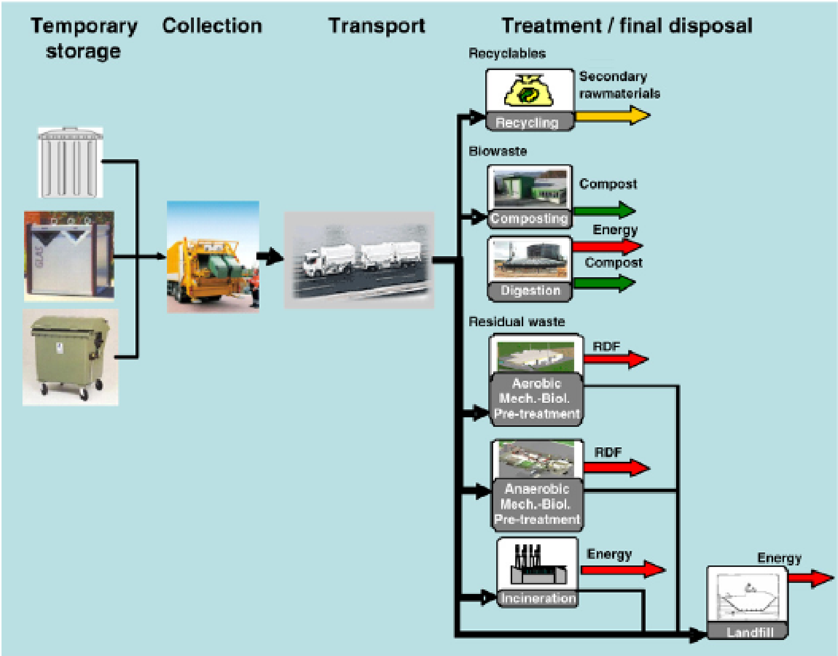

Figure 1: An Integrated Waste Management System Containing all the Background Modules of the LCA-IWM Assessment Tool

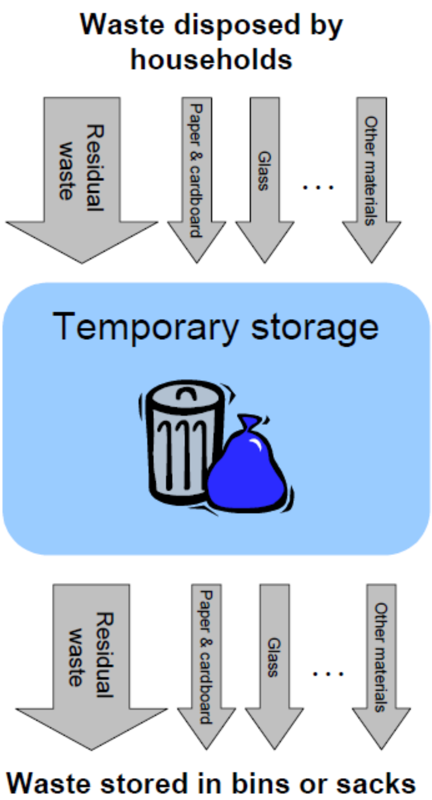

Figure 2: Temporary Storage diagram

Having concerned the design of temporary storage municipalities, there are two relevant decision options as follows:

- **Volume of used containers**: Depending on the collection system, it can have a variety of sizes of bins and containers varying from single-household bins to multi-household containers.
- **Collection frequency**: The collection frequency determines the number of used bins and sacks. The higher the collection frequency, the lower the number of necessary collection repositories.

Concerning the main collection streams within the waste management system (residual waste, paper and cardboard, glass, metals, plastics and composites, packaging material and bio-waste), there are three different types for the temporary storage that can be selected

- Sack collection (mainly kerbside collection),
- Collection with bins with less than 500 litres volume (mainly kerbside collection) and
- Collection with bins with more than 500 litres volume (kerbside, at transfer station or at central collection sites).

Table 1 shows the volume and materials that can be selected in the LCA-IWM assessment tool.

The remaining four waste types (garden waste, hazardous waste, WEEE and bulky waste) are usually not collected with sacks or small bins due to their bulky character (garden waste, WEEE and bulky waste) or due to the importance of central collection in case of the hazardous waste. Therefore a lot of different container types (e.g. sometimes no container in case of separate and infrequent collection of bulky or garden waste) are in use. As the main material consumption and bin costs in WMSs come from small bins, it was acceptable to neglect the use of these bins.

Table 1: Volume and Material of Sacks and Bins available in LCA-IWM tool

Sacks		Containers with volume below 500 litres		Containers with volume above 500 litres	
Volume (l)	Material	Volume (l)	Material	Volume (l)	Material
60	PE	80	HDPE/Steel	660	HDPE
80	PE	120	HDPE/Steel	770	HDPE/Steel
100	PE	240	HDPE	1100	HDPE/Steel
				2500	HDPE/Steel
				3200	Steel
				5000	Steel

PE – Polyethylene

HDPE – High density polyethylene

Steel – Galvanized steel plate

The estimation of the necessary number of bins and sacks depends on the following parameters:

- Percentage of inhabitants using 1. sacks, 2. small bins (volume below 500 l) or 3. big bins (volume higher than 500 l) for each fraction
- Collection frequency for each type of temporary storage, sector and fraction (per year)
- Average filling rate of bins: This correction factor considers the fact that bins are not totally filled at every collection cycle (e.g. due to seasonal variation)
- Waste density per fraction (constant parameters) Based on these inputs and on the separated collected waste quantities the number of necessary bins can be calculated.

2. Collection and Transportation

Collection and transport module in the LCA-IWM assessment tool includes the:

- Collection of non-separated and separated solid waste and recyclables in an urban area and

- The transportation of the collected waste and recyclables to processing and disposal facilities.

Figure 3 shows the scheme of this process. Input contains the material in bins and sacks at the time of collection which will be transferred to the provided facility. The direct impacts of this process contain the

- traffic emissions deriving from the necessary transports,
- the economic costs covering the costs for personnel, truck fleet (purchase and maintenance costs), fuel cost etc. and
- Some social impacts with regard to the social acceptability, equity and function of the collection and transportation management in the waste management system.

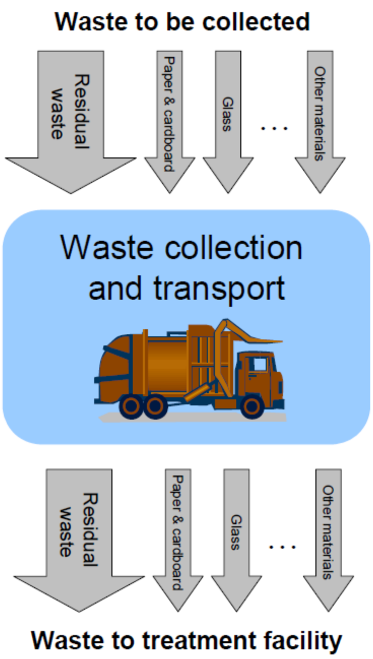

Figure 3: Collection and Transport Diagram

The model applied in the Assessment Tool was created to make a realistic estimation of the necessary:

- Transport distances (as calculation basis for fuel consumption and social impacts (e.g. noise));
- expenditure of time for Collection and Transport (for personnel costs estimation); and finally

- the required truck fleet capacity (e.g., for calculation of purchase cost).

Transportation by road was assumed for this module which covers the emptying of bins and sacks in the community and carrying collected waste to the facility or treatment plant. Figure 4 shows the collection and transport scheme with an existing transfer station. The user can specify the applied collection and transport scheme in the following way:

- Average distance from the garage to the first pick-up in a defined sector;
- Average distance from the (eventual) transfer station to the first pick-up in a defined sector; and
- Average distance from the transfer station to the garage.

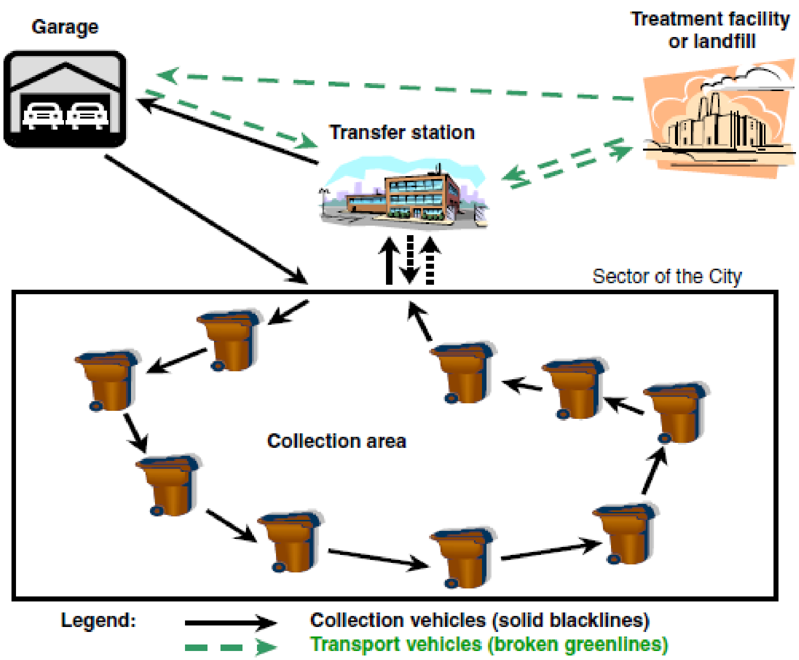

Figure 4: Collection and Transport Scheme with Transfer Station

3. Treatment, recycling and final disposal

The following waste treatment processes have been modelled within the developed assessment tool:

- Composting of separately collected organic waste;

- Digestion of separately collected organic waste;
- aerobic mechanical-biological pre-treatment (MBP) of mixed/ residual waste;
- anaerobic MBP of mixed/residual waste;
- incineration with energy recovery of mixed/residual waste;
- recycling of separately collected materials: paper and cardboard, glass, metals, plastics, packaging waste, mixed dry recyclables (MDR) and waste electric and electronic equipment (WEEE);
- landfilling of mixed/residual waste.

The technologies selected for modelling are the ones most commonly used in modern waste management systems in Europe. They are considered as state-of-the-art, but already broadly verified treatment methods. Input data on chemical properties of waste is a basis for modelling of mass balances of waste treatment processes. The chemical composition determines important features of waste such as biodegradability rate or calorific value. Contaminants content in waste (heavy metals, chloride, fluoride, etc.) renders the quality of products derived from the waste. In the Assessment Tool waste properties are provided as default values mostly based on German data.

For all waste fractions, either separately collected or within the residual waste, characteristics in terms of water and organic content, degradability and contaminants are provided. For organic wastes a distinction is made between separately collected and organic waste within the residual waste.

The treatment and disposal modules for residual/mixed waste and organic waste are dependent on the detailed composition of the input waste flow. The recycling modules are dependent on the waste input on a sub-flow level (e.g., paper of de-inking quality, cardboard and contamination for the paper and cardboard fraction). The detailed composition of the sub-flows is not assumed to be influencing the (mostly environmental) effects of the recycling system.

On the basis of an extensive literature review, a cost function, based on a statistical method, was chosen for each type of facility, both for initial cost and for operation cost. A detailed analysis of the used method is given in the sources: Tsilemou & Panagiotakopoulos 2004 and 2005. The development of “exact” curves, which would be useful for all possible cases in all EU countries are introduced using as a rough estimation in this assessment tool which shows below.

Table 2: Suggested Cost Curves for treatment and disposal facilities

Type of Treatment Facility	Suggested Cost Functions: Initial Capital Investment (€)[a]	Suggested Cost Functions: Operating Cost (€/ton)[a]	Range (ton/year)
Incineration[b]	$y = 5{,}000 * x^{0.8}$	$y = 700 * x^{-0.3}$	$20{,}000 \le x \le 600{,}000$
Aerobic Mech. -Biol. Pre-treatment	$y = 1{,}500 * x^{0.8}$	$y = 4{,}000 * x^{-0.4}$	$7{,}500 \le x \le 250{,}000$
Anaerobic Mech. -Biol. Pre-treatment	$y = 2{,}500 * x^{0.8}$	$y = 5{,}000 * x^{-0.4}$	$7{,}500 \le x \le 250{,}000$
Anaerobic Digestion	$y = 34{,}500 * x^{0.55}$	$y = 17{,}000 * x^{-0.6}$	$2{,}500 \le x \le 100{,}000$
Composting	$y = 2{,}000 * x^{0.8}$	$y = 2{,}000 * x^{-0.5}$	$2{,}000 \le x \le 120{,}000$
Landfill [c]	$y = 6{,}000 * x^{0.6}$	$y = 100 * x^{-0.3}$	$500 \le x \le 60{,}000$
	$y = 3{,}500 * x^{0.7}$	$y = 150 * x^{-0.3}$	$60{,}000 \le x \le 150{,}000$

[a] Price level 2004

[b] The incineration cost function does not include expenditure for disposal of incineration residues.

[c] The landfill cost function corresponds to mixed inflowing municipal waste; it does not appropriate for landfilling of residuals from other facilities.

Appendix II: The LCA-IWM Assessment Tool – Assessment Modules

The goal of the assessment module in the LCA-IWM tool is the sustainability of waste management. Therefore, all economic, social and environmental aspects are included into the decision-making process which displays the results separately.

Most decisions in European communal waste management planning are based on costs alone. One of the goals of the LCA-IWM project was to develop a tool that enables the making of sustainable decisions in the field of waste management planning. Thus, apart from the costs (or economic sustainability), the other pillars of sustainability (environmental and social) are incorporated into the decision-making process. Currently models are in use which incorporate environmental effects into economic evaluations by internalising these external costs (costs for the society which do not show up in prices of products or services). In the opinion of the authors such a method does not necessarily support the transparency of the outcomes of an assessment. Moreover a methodological approach for internalising social effects of waste management systems does as yet not exist. Thus in the LCA-IWM Assessment Tool the environmental, social and economic results are displayed separately, without making an attempt to aggregate all outcomes into one single monetary number.

1. Environmental Assessment

General objectives for environmental sustainability can be summarized as rational resource consumption and reduction of environmental pollution. Hence, the same goals are valid for environmental sustainability in waste management adopted within the LCA-IWM project.

1.1 Selection of Environmental Criteria based on LCIA Method

The selection of criteria for the environmental assessment in this tool was based on the one hand on the fundament of the life cycle impact assessment (LCIA) method, and on the other hand on the requirements and targets of the European waste policy. A number of life cycle impact assessment methods have been developed in the past years. Within the LCA-IWM project, the selected method was the method based on Guine et al. (2001). Within this LCIA method the baseline impact categories are recommended to be used for all LCAs. After the performance of a ‘‘screening’’, in which a minimum and a maximum recycling scenarios for a case study were compared, the following LCA impact categories were determined as relevant for assessment of waste management scenarios and thus selected as assessment categories in the LCA-IWM project: 1) depletion of abiotic resources; 2) climate change; 3) human toxicity; 4)photo-oxidant formation; 5) acidification; and 6) eutrophication.

1.1.1 Depletion of abiotic resources

Abiotic resource depletion is one of the most frequently discussed impact categories and there is consequently a wide variety of methods available for characterising contributions to this category. Depending on the definition the areas of protection of this category are both natural resources only, or natural resources, human health and the natural environment. Application of this criterion within waste management assessment allows to account for positive aspects of the recovery of waste, both in form of recycling as well as energy recovery. The resources that are saved due to recycling and recovery replace abiotic resources that would have to be otherwise extracted.

The indicator **Abiotic depletion** is calculated according to the following formula:

$$Abiotic\ depletion = \sum_i ADP_i \times m_i$$

Where: ADP_i - Abiotic Depletion Potential of resource i (characterisation factor, kg antimony eq./kg)

m_i - quantity of resource i extracted (kg)

The Abiotic Depletion Potential depends on ultimate reserves and rates of extraction of a given resource. ADP is defined as follows:

$$ADP_i = \frac{DR_i}{R_i^2} \times \frac{R_{ref}^2}{DR_{ref}}$$

Where: ADP_i - Abiotic Depletion Potential of resource i (kg antimony eq./kg)

R_i - ultimate reserve of resource i (kg)

DR_i - extraction rate of resource i (kg/year)

R_{ref} - ultimate reserve of reference resource, antimony (kg)

DR_{ref} - extraction rate of reference resource (kg/year)

1.1.2 Climate Change

Typical emissions for waste management that contribute to global warming potential include fossil carbon dioxide, dinitrogen oxide and methane. Thus both thermal and biological waste treatment processes are relevant contributors within this criterion. Below the quantification method for climate change is given.

Global Warming Potentials (GWP) are used as characterisation factors to assess and aggregate the interventions for the impact category climate change. A greenhouse gas indicator is derived from two basic properties of each gas. The first is its ability to reflect heat. The second is how long the gas remains in the atmosphere, that is, how long it may act to reflect heat. These properties are then compared to the properties of carbon dioxide and converted into carbon dioxide equivalents. Then the individual equivalents are added together, for the overall greenhouse gas indicator score that represents the total quantity of greenhouse gases released. Thus the overall indicator is calculated in the following way:

$$Climate\ Change = \sum_i GWP_i \times m_i$$

Where: GWP_i - Global Warming Potential of the substance i

m_i - mass of substance i released in kg

Climate Change is the indicator result, which is expressed in kg CO_2-equivalents. More details description of this indicator can be found in the deliverables of the LCA-IWM project.

1.1.3 Human Toxicity

Inadequate waste management practices can pose considerable thread on human health. Waste contains toxic substances which have to be managed in a way to minimize their penetration to the environment. Emissions from waste management with the most significant impact within this category include: heavy metals (especially hexavalent chromium, mercury, and lead, nickel and copper), dioxins, barium and antimony.

Indicator human toxicity is calculated according to the following formula:

$$Human\ Toxicity = \sum_{i} \sum_{ecomp} m_{i,ecomp} \times HTP_{i,ecomp,t}$$

Where: $HTP_{i,ecomp,t}$ - the Human Toxicity Potential, the characterisation factor for the human toxicity of substance i emitted to emission compartment ecomp. for the time horizon t

m_i - the emission of substance i to compartment ecomp (kg) mass of substance i released in kg,

More details description of this indicator can be found in the deliverables of the LCA-IWM project.

1.1.4 Photo-oxidant Formation

Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops. The relevant areas of protection are human health, the man-made environment, the natural environment and the natural resources. A photochemical ozone indicator is derived by finding conversion or reactivity factors for Volatile Organic Compounds VOCs. This is then used to convert the inventory VOCs into ethylene equivalents.

$$\text{Photo} - \text{oxidant Formation} = \sum_{i} POCP_i \times m_i$$

Where: $POCP_i$ - the photochemical ozone creation potential of the substance i

m_i - the emission of substance i

Photochemical Ozone creation Potential (POCPs) were originally developed to assess various emissions scenarios for volatile organic compounds. POCP of VOC is defined as a ratio between the change in ozone concentration due to a change in emission of that VOC and the change in the ozone concentration due to a change in the emission of ethylene, expressed as a formula:

$$POCP_i = \frac{a_i/b_i}{a_{C2H4}/b_{C2H4}}$$

Where: ai - is the change in ozone concentration due to change in the emission of VOC i

Bi - is the integrated emission of VOCi up to that time

a_{C2H4} and b_{C2H4} contain these parameters for ethylene (the reference substance.)

The characterisation factors for have been extended to add effects of NO_x and few another inorganic substances.

1.1.5 Acidification

As for waste management the major impacts within this category arise from nitrogen oxides emissions from thermal processes and ammonia from biological processes and sulphur oxide emissions from electricity production.

Calculation of acidification is based on the following formula:

$$Acisification = \sum_i AP_i \times m_i$$

Where: AP_i - the acidification potential of the substance i

m_i - the emission of substance i

Potential acid deposition can be expressed in terms of potential H+- equivalent. Thus potential acidifying is aggregated on the basis of chemicals capacity to form H+ ions. For example, one molecule of SO2 yields two H+ ions, while one molecule of NOx yields one H+ ion.

Thus originally the acidification potential (AP) of substance i has been defined as a number of H+ ions produced per kg substance relative to SO2:

$$AP_i = \frac{n_i}{n_{SO_2}}$$

Where: n_i (mol kg-1) represents number of H+ ions that can potentially be produced per kg substance i;

n_{SO2} (mol kg-1) represents the number of H+ ions that can potentially be produced per kg SO_2;

1.1.6 Eutrophication

Eutrophication covers all potential impacts of excessively high environmental levels of macronutrient, the most important of which are nitrogen and phosphorus. Nutrient enrichment may cause an undesirable shift in species composition and surplus biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may render surface waters unsuitable for drinking water. An increased biomass production in aquatic environment results in additional oxygen consumption for biomass decomposition (measured as BOD). Thus emissions of biodegradable matter will have the same effects as enhanced nutrient emissions, and thus BOD is also accounted for as eutrophication potential. The areas of protection are the natural environment, natural resources and man-made environment. Referring to the waste management the Eutrophication potential is attributed to atmospheric emissions of NOx and ammonia, as well as P an N to water from biological processes.

The indicator eurtrophication is calculated according to the following formula:

$$\text{eutrophication} = \sum_i EP_i \times m_i$$

Where: EP_i - the eutrophication potential of the substance i

m_i - the emission of substance i

Eutrophication is the is the indicator result, which is expressed in kg PO_4^{3-} equivalents

EP_i, reflects a substance's potential contribution to biomass formation, according to the formula:

$$EP_i = \frac{v_i / M_i}{v_{ref} / M_{ref}}$$

Where: v_i and v_{ref} are potential contributors to Eutrophication of one mole of substance I and ref (i.e. PO_4^{3-}) and

Mi and Mref (kg mol-1) are the mass of i and ref (i.e. PO_4^{3-}).

EPs are based on the average chemical composition of the aquatic organisms: $C_{106}H_{263}N_{16}P$, so that in this approach 1 mole of P biomass requires 16 mole of N. The characterisation factor for COD is based on the fact that when 1 mole of biomass is released it requires 138 moles of O_2 for degradation In the past years efforts have been made to introduce site and region modelling of Eutrophication (analogically to Acidification). However, this method is not fully developed yet and thus the generic Eutrophication potentials will be used within this LCA-IWM project.

1.1.7 Normalization and Aggregation of the Environmental Indicators

According to the principles of LCA, the (i) inputs (in terms of raw materials and energy) and (ii) outputs (in terms of emissions to air, water and solid waste) are calculated for each ''life stage''. This process is called inventory analysis. The results of the inventory are aggregated over the entire life cycle. By multiplying single emissions and resources by characterisation factors they can be attributed to the mentioned LCA-based indicators.

The total characterized values of these six indicators are expressed in inhabitant equivalents (IE). This step, the normalisation, enables a comparison between the different indicators. It should be kept in mind, though, that 1 IE in, e.g., the indicator climate change does not have the identical physical meaning as 1 IE in Eutrophication. In the Assessment Tool the indicator values are shown for all six LCA-based criteria separately.

To enable a condensed overview, the six indicators are aggregated by using weighting factors and relating the total impact of a planned scenario to the existing scenario. Though this condensed result does not have a physical meaning, it provides means of comparison between various scenarios. The EU-waste policy based criteria show the user whether or not the valid targets are met in the planned scenarios.

1.2 Criteria based on Specific Targets of EU Waste Policy

The targets of the Waste Framework Directive concerning municipal waste are accounted for within the LCA-based criteria of this project. Further waste policy based criteria concern:

- packaging recovery and recycling targets,
- targets for diversion of organic waste fraction from landfilling
- collection and recovery targets of waste of electric and electronic equipment (WEEE)
- collection of hazardous waste.

In this section, only details of packaging recovery and recycling targets are mentioned due to this is the only criterion that uses in this paper.

1.2.1 Packaging recovery and recycling targets

The Directive 94/62/EC on Packaging and Packaging Waste (Packaging Directive) is concerned with specific recovery and recycling targets at the national level, thus it is not binding for municipal solid waste on a communal level. However, since the national targets can only be achieved if all the administrative units within the national system contributes to the general target. The municipality itself may have targets that vary from the ones prescribes by the Packaging directive. Within this project targets of the Packaging directive will be considered as default for municipal waste management planning. The targets to be achieved by the end of 2008 are given by European Parliament and Council (2004). This data is used as a default target in this LCA-IWM tool. The targets are divided in recycling and recovery targets.

Table 3: Recycling and recovery targets in the Packaging Directive

Target	First period EU	second period EU
Overall recovery	Min. 50%, max. 65%	Min. 60%
Overall recycling	Min. 25%, max. 45%	Min. 55%, max. 80%
Material specific recycling:		
- Glass	15%	60%
- Paper/Board	15%	60%
- Metals	15%	50%
- Plastics	15%	22.5%
- Wood	-	15%
Targets attained by	June 20011	December 20082

2. Economic Assessment

Economic sustainability implies the least expensive waste management system provided that it secures sufficient revenues to ensure:

- An economically sound and continuous operation; and
- Coverage of all aftercare expenses for a period stipulated by law (not less than 30 years after closure).

Within the LCA-IWM Assessment tool the following pre-conditions are taken into consideration as well:

- economic sustainability is related (and refers) to a specific technical system, a specific time horizon and a specific decision-maker;
- a system operates in an economically sustainable manner if it covers all its expenses and it expects to do so over the horizon of the analysis (50–60 years); and
- if the system covers part of its expenses through subsidies, it could be considered sustainable only if there is a guarantee that these subsidies will continue to be available ‘‘forever’’.

2.1 Selection of economic sustainability criteria and indicators

A central issue in the economic sustainability assessment is the distinction between costs incurred by the municipalities in delivering the service of solid waste management and revenue generated by recovered energy or materials or revenue from municipal rates and tipping fees. This is because the forcing factors for the costs are totally different from those for the credits and the revenues. The factors affecting municipal solid waste management system (MSWMS) costs are different from those affecting prices for recovered materials or tipping fees and user charges. From a management point of view, aiming at improving the system, it is necessary to separate cash out-flows from revenues (cash inflows), since the ‘‘corrective’’ actions for the two are different, e.g., the reduction of collection costs requires different actions on the part of the municipality than the increase of charges. Based on the above, the Economic Sustainability is assessed with the following criteria and indicators:

Economic efficiency:

At both the sub-system level and the system level, measured by;

- cost per ton or per household or per person (for entire WMS and per subsystem);
- revenue from recovered material and energy;
- MSWMS cost as % of Gross National Product (GNP) of the city; and
- Diversion between revenue and expenditures for MSWMS.

Equity:

The purpose of this criterion is to examine the extent to which the economic burden is distributed equitably among neighborhoods and citizens. It is measured by;

- Cost per person as % of minimum wage per person; and
- Cost per person/income per person.

Dependence on subsidies: The economic evaluation should take into consideration the financial sources for setting up and operating the system. The extent to which the municipality is self-sustainable or relying on ‘‘external’’ sources, i.e., on grants and subsidies, is measured by:

- Subsidies or grants per person.

2.2 Economic sustainability assessment

The initial capital investment of each subsystem and of the whole system is not an indicator of efficiency. It is, however, a significant additional factor if one examines the economic feasibility of a proposal for a new facility. All costs are transformed into equivalent annual costs, taking into consideration the time value of money (cost of capital). For the quantification of both the capital and operating costs, the user may not have adequate data available. In this case default values (capacity dependent) are offered. These are based on an extensive literature survey, which was undertaken in the LCA-IWM project reported by Den Boer et al. (2005), and Tsilemou and Panagiotakopoulos (2004, 2005).

3. Assessment Outputs

The outputs of the LCA-IWM assessment tool can be divided to three spheres: support information, assessment results and condensed results. The support information consists of intermediate results of the assessments calculations which are used in the further assessment process. These outputs, although they are not a part of the assessment result, provide the user with valuable feedback on his modelled scenarios. Examples of support information are numbers of bins, employees, vehicles and waste flows.

The assessment outputs are the results as described in the previous sections. For the environmental assessment these are according to the LCA-methodology characterized and normalised impacts in the before mentioned impact categories. The additional two ‘EU policy’ criteria show whether and to the extent the specific targets for the considered country and year have been met. The economic assessment provides with total yearly costs and investment costs, which are also related to various fields of interest (e.g., subsidies, minimal wage, revenues).

Although the assessment tool is not intended to aggregate the environmental, economic and social result to single number outcomes (the authors advocate the verbal argumentative approach), the outputs are provided in a condensed manner as well. In a simple arithmetic step the outcomes in the environmental, economic and social assessment are bundled into dimensionless scores, which are related to the current (first) scenario. These condensed results do not have a physical meaning and are merely an option for a swift comparison between various scenarios. A weighting of environmental and social versus economic impacts is not part of the tool; this is strongly dependent on the user's value system and therefore left up to the user.